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DECISION-MAKING GUIDE
FOR THE PROPOSED COAST GUARD
DIFFERENTIAL GLOBAL POSITIONING SYSTEM

by

Robert J. Wilson

June, 1991

Thesis Co-Advisors: Dan C. Boger
                                        Kurt Schnebele

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The Coast Guard has begun an initiative to deploy a nationwide Differential Global Positioning System (DGPS) to support Coast Guard missions and to enhance maritime safety in harbor navigation. DGPS service is expected to provide accuracy to within ten meters (95% of the time) to suitably equipped vessels. It would do this by broadcasting corrections to GPS navigation satellite signals, thereby improving accuracy by a factor of ten over standard GPS.

The primary emphasis of this thesis is to show how decision making and planning for the DGPS project may be aided by comparing technological alternatives using Cost-Effectiveness Analysis (CEA). This method is essentially a means of quantifying effectiveness per dollar of cost. The author consolidates the discussion of key issues within one document, identifies the technical decision criteria, estimates alternative system life-cycle costs, and makes a preliminary finding as to the merits of radiobeacon transmission over a dedicated satellite channel. In order to quantify effectiveness, many performance criteria are consolidated under five "figures of merit": accuracy, availability, coverage, integrity, and adaptability. The inclusion of user equipment prices in life-cycle costs proves to be critical to the preliminary finding in favor of the radiobeacon-based alternative. This CEA model is especially suited to decision making in an environment of technological and policy change, since it can be easily refined and updated over the predicted four year implementation period.

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for the Proposed Coast Guard
Differential Global Positioning System

by

Robert J. Wilson
Lieutenant, United States Coast Guard
B.S., United States Coast Guard Academy, 1980

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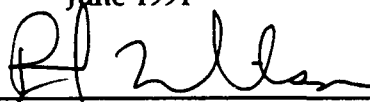of the requirements for the degree of

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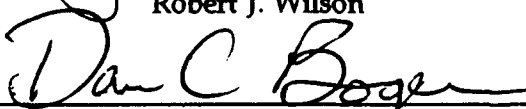
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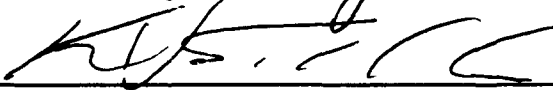NAVAL POSTGRADUATE SCHOOL
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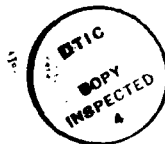Kurt Schnebele, Captain, NOAA, Thesis Co-Advisor

_____
David R. Whipple, Chairman
Department of Administrative Sciences

ABSTRACT

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The primary emphasis of this thesis is to show how decision making and planning for the DGPS project may be aided by comparing technological alternatives using Cost Effectiveness Analysis (CEA). This method is essentially a means of quantifying effectiveness per dollar of cost. The author consolidates the discussion of key issues within one document, identifies the technical decision criteria, estimates alternative system life-cycle costs, and makes a preliminary finding as to the merits of radiobeacon transmission over a dedicated satellite channel. In order to quantify effectiveness, many performance criteria are consolidated under five "figures of merit": accuracy, availability, coverage, integrity, and adaptability. The inclusion of user equipment prices in life-cycle costs proves to be critical to the preliminary finding in favor of the radiobeacon-based alternative. This CEA model is especially suited to decision making in an environment of technological and policy change, since it can be easily refined and updated over the predicted four-year implementation period.

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I. INTRODUCTION

A. OVERVIEW

The basic objective of any engineering design effort is to develop a system that will perform its intended function in the most cost-effective manner. This requires recognition of many engineering and management considerations when making decisions. An important tenet of systems engineering is that it is not sufficient to design efficient subsystems and put them together. Rather, the effort seeks to optimize the performance of the system as a whole. All elements of the system should be addressed on an integrated basis, with trade-offs quantified to optimize system design. [Ref. 1:p. 137]

Decision making for the proposed Coast Guard Differential Global Positioning System (DGPS) will require just this sort of engineering and managerial analysis. The research questions for this thesis were:

- How should systems engineering and economic methodologies be applied to the proposed Coast Guard DGPS project?

- What are the decision/selection criteria?

- For the alternatives considered, which does the author's Cost-Effectiveness Analysis (CEA) indicate is best?

    The research approach to answer these questions consisted of:

- Surveying available literature from various disciplines relevant to this DGPS project, including: navigation, electronics, telecommunications, economics, systems engineering and management.

- Identifying Coast Guard objectives and DGPS issues, with consideration of existing and proposed technology.

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- Applying CEA so as to explore the suitability of the method and decision criteria to the project in general.

- Identifying a preferred alternative based upon the author's weighting of the decision criteria.

B. SCOPE

The thrust of this thesis is to show how decision making may be facilitated by using CEA to compare technological alternatives. This method is essentially a means of quantifying effectiveness per dollar of cost. Two broadcast alternatives (a radiobeacon broadcast and a dedicated satellite channel broadcast) are analyzed to illustrate the procedure.

The primary purpose is *not* the recommendation of a definitive DGPS service design. A definitive solution would require the analysis of a pool of alternatives too large to do justice to here. Also, the CEA results are based upon the author's necessarily subjective weighing and rating of the two systems' performance parameters. Although the conclusions of this thesis indicate that the radiobeacon alternative seems preferable to the satellite alternative, an operational decision should also incorporate the input of experienced individuals with other perspectives. Furthermore, the context of the problem is still developing, and a final decision on the "best" DGPS configuration would be inappropriate at this early stage.

Instead of supplying an immediate answer, the CEA model may aid the evolution of a DGPS service design by facilitating iterative *systems engineering* to gradually produce an optimal solution. Systems engineering is a process for system development: it begins when a need becomes apparent and continues

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through deployment of a suitable system in the field. As the project progresses through its life cycle, engineering decisions will be made that could have a significant feedback effect on what has already been accomplished. The model will encourage consideration of changes or new information to reevaluate the design.

The structure for analyzing the *effectiveness* of a DGPS system is proposed in Chapter V.B., Tables 5-1 and 5-2. This model is a simplified representation of the real world which is adapted to abstract the features of the problem being analyzed. The model, in itself, is not the decision maker, but a tool that presents the necessary data in support of the decision-making process [Ref. 1:pp. 11-43]. It incorporates the following criteria:

- Accuracy: update rate, latency, reference station spacing

- Availability: component dependability, resistance to EMI, resistance to ionospheric variations, resistance to multipath and signal obstruction, graceful degradation

- Coverage: harbor and harbor approaches and coastal phase, ocean phase, inland phase

- Integrity: timeliness, index of safety

- Adaptability: international compatibility, interagency compatibility, technical flexibility, open systems interoperability, spectral efficiency, institutional impact.

Logistics and procurement strategy are not considered in detail. Project planning and several issues surrounding DGPS network design are discussed, but no detailed planning proposals are developed.

C. RELEVANCE OF DGPS TO THE COAST GUARD

1. Historical Precedent

Coast Guard involvement in providing navigation services originated with the incorporation of the Lighthouse Service in 1939. The Lighthouse Service had a major role in developing radio-equipped airways. The Coast Guard integrated the Lighthouse engineers with its Office of Engineering, and so acquired a great deal of technological experience in the emerging field of electronics. In 1946, when the Navy needed a coordinator for the troubled project that was to become Loran, it called on the Coast Guard. From this beginning, the Coast Guard has grown to become the Federal provider of long range, terrestrially-based radionavigation systems. [Ref. 1:pp. 96-98]

2. Existing Responsibility

The Coast Guard has the responsibility to provide for safe and efficient navigation as follows:

> In order to aid navigation and to prevent disasters, collisions, and wrecks of vessels and aircraft, the Coast Guard may establish, maintain, and operate... electronic aids to navigation systems (a) required to serve the needs of the armed forces of the United States... or (b) required to serve the needs of the maritime commerce of the United States; or (c) required to serve the needs of the air commerce of the United States as requested by the Administrator of the Federal Aviation Administration. [Ref. 2]

Under the provisions of this law, the Coast Guard now operates the radiobeacon, Loran-C, and Omega long range radionavigation systems.

Additionally, the Coast Guard already has been appointed by the Department of Transportation (DOT) as lead agency for the GPS civil user interface. This includes Coast Guard coordination of the Civil GPS Interface

Committee, a forum for the exchange of information and views on GPS matters. The Coast Guard is also responsible for disseminating Department of Defense (DOD) originated GPS information through the operation of the GPS Information Center.

3. Growing Need for DGPS

At the least, DGPS-level accuracy is needed for the Coast Guard's own use to most efficiently perform Coast Guard missions. Most prominent are the needs for the positioning of buoys and the positioning of ships participating in Vessel Traffic Services (VTS) [Ref. 3:p. 2]. Also, DGPS has the potential to be used by the general public for radionavigation in restricted waters, particularly if it is integrated with real-time display on electronic charts [Ref. 4:p. 306,318]. This could allow higher levels of vessel safety or economic efficiency in harbors, especially in darkness or unfamiliar ports (see Chapter III).

Historically, radionavigation initiatives have been accelerated by focused public interest in oil spill prevention. A major impetus for speedy completion of the Coast Guard Loran-C system was anticipation of increased tanker traffic from the Trans-Alaska pipeline [Ref. 5:p. 142]. In response to recent oil spills, the demand for improved accident-prevention measures has grown once again. The rationale is well stated by William J. Cook in an essay in *U.S. News and World Report*:

> ... *Exxon Valdez* was out of range of the Coast Guard's simple radar system when the accident happened. And most U.S. oil ports, unlike airports, don't even have radar. The Coast Guard, in fact, shut down its New York harbor radar two years ago for lack of money. Following the *Exxon Valdez* and *Mega Borg* accidents, we'll probably end up with an expensive technofix--millions of dollars' worth of equipment and chemicals pre-positioned near places where

oil spills might occur. We might get better results for less money if we emulated aviation and invested more in improved tanker design and maintenance, crew training and accident-prevention procedures. What sense does it make for a nation to spend a fortune sending the Navy to the Persian Gulf to keep oil moving when it spends so little to keep tankers steaming safely? [Ref. 6:p. 15]

Since the publishing of this essay, the Oil Spill Pollution Act of 1990 was signed into law; it included provisions for improvement of VTS Prince William Sound (site of the *Exxon Valdez* spill), to include DGPS components.

4. Coast Guard Distinctive Competence

The Coast Guard is well situated to meet the forecasted need for a nationwide DGPS system. It has the necessary "distinctive competence", a term used by Bragaw in *Managing a Federal Agency*:

First, the Coast Guard identifies national needs in its area. These needs are the demands of the various publics to be served--its constituents.... Second, the Coast Guard identifies the means--its distinctive competence--that ideally equip it to fill these needs. These means are the type and number of its human and physical resources--the very "character" of the organization. [Ref. 5:p. 42]

Providing DGPS service would advance Coast Guard organizational expertise in support of the strategic goal of continuing to serve the nation's public long range navigation needs into the next century. The Coast Guard can build on the experiences of its other radionavigation systems, which provide the organizational "distinctive competence" to provide DGPS service. In addition, over ten years of research, development, testing and evaluation of DGPS have been done by the Coast Guard R&D Center [Ref. 3:p. 2]. In summary:

The structure should seek to take on those programs and services that the Coast Guard can carry out more effectively than anyone else. The distinctive competence and credibility of the Coast Guard should be important factors in

developing proactive and innovative public policy and programs. [Ref. 5:pp. 36-37]

D. CHAPTER OUTLINE

A technical background necessary for a basic understanding of DGPS issues

is provided in Chapter II. This includes discussions of radionavigation in general,

GPS, DGPS, and system architecture.

The remainder of this study directly follows the CEA methodology. The

essential steps of CEA analysis adapted for DGPS implementation planning, and

the chapters they are addressed in, are as follows:

- define system objectives (Chapter III)

- state evaluation assumptions (Chapter III)

- identify essential mission requirements (Chapter IV)

- list alternatives (Chapter IV)

- establish effectiveness measures (Chapter V)

- evaluate alternatives' overall effectiveness (Chapter V)

- develop cost data (Chapter V)

- assess effectiveness and cost risks (Chapter VI)

- perform cost-effectiveness computations (Chapter VI)

- perform sensitivity analysis (Chapter VI) [Refs. 3, 4, 5].

II. TECHNOLOGICAL BACKGROUND

A. RADIONAVIGATION

1. General

Radio signals have been used for decades to provide directional homing and navigational lines of position. The basic purpose of "navigation" is guiding the safe movement of a vehicle from one place to another. "Positioning", on the other hand, is the process of determining, at a particular point in time, the precise location of a vehicle or site. The subtle but significant difference hinges upon the greater safety burden on navigation. International agreements governing use of the radio frequency spectrum include allocations for "radionavigation" and "radiolocation" services. The following terms should be understood in the sense used by the Radio Regulations of the International Telecommunication Union (ITU) [Ref. 7:pp. 1-3, 1-7]:

- Radiodetermination: The determination of the position, velocity and/or other characteristics of an object, or the obtaining of information relating to these parameters, by means of the propagation properties of radio waves; includes navigation and positioning.

- Radionavigation: Radiodetermination used for the purposes of navigation, including obstruction warning.

- Radiolocation: Radiodetermination used for purposes other than those of radionavigation.

- Radiodetermination Satellite Service (RDSS): a *radiocommunication* service involving the use of radiodetermination and the use of one or more space stations [Ref. 8:p. 63].

In the United States the Federal government has long provided navigation services to the general public. The Department of Transportation is responsible for civil navigation. In addition, the Department of Defense provides navigation services to the military, some of which are used by the civilian community. There are also a number of privately developed and operated radiolocation systems. They operate in the radiolocation frequency bands using a variety of techniques; they are used where public radiodetermination coverage is not available or sufficiently accurate. [Ref. 7:pp. 1-3, 1-7]

2.   **Radionavigation System Parameters**

Description and comparison of the various radionavigation systems is facilitated by the use of standard parameters. The interested reader may refer to Appendix A of the Federal Radionavigation Plan (FRP) for a complete description of the ten prescribed parameters. However, three of these (accuracy, availability, and integrity) are used extensively in the following chapters and should be understood in the sense of the definitions contained in the FRP, as follows:

a.   Accuracy

As used in navigation, accuracy is the degree of conformance of a measured position to the true position of the craft at that time. Accuracy is a statistical measure of performance, and is *meaningless* unless it includes a statement of the uncertainty in position which applies. Two-dimensional horizontal accuracies in this paper are normally "2drms": 95% of positions provided by the navigation system will be within the given distance of the true location.

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Also, accuracy must be related to one, two, or three dimensions [Ref. 9:p. A-1]:

- When specifying one-dimensional linear accuracy (altitude, for example), the 95 percent confidence level is equivalent to "2 sigma". Alternatives used in various references are "1 sigma" (68%) or "Linear Error Probable" (LEP: 50%). [Ref. 10:p. 3-5]

- When two-dimensional (e.g., horizontal) accuracies are cited in this study, the "2drms" (distance root mean square) uncertainty estimate will be used. Depending on the assumptions used, this statistical measure can vary between 98 and 95 percent. *As used herein, "2drms" accuracy will be at 95 percent.* Alternative measures include: "2 sigma" (86%), "1 sigma" (39%), and "Circular Error Probable" (CEP: 50%). CEP may be roughly converted to 2drms by multiplying by 2.5 [Ref. 9: p. A-2].

- When three dimensions are relevant, the linear accuracy in the vertical axis is often considered separately from the two dimensional horizontal accuracy. Alternatively, some references assume equal variation in all dimensions and use Spherical Error Probable (SEP: 50%) or one, two, or three sigma (about 20%, 79%, and 97%, respectively). [Ref. 10:p. 3-5]

b. *Availability*

Signal availability is the percentage of time that navigational signals transmitted from external sources are available at the user's antenna. It is a function of both the physical environment and the transmitter facilities. [Ref. 9:p. A-2]

c. *Integrity*

As used in radionavigation literature, integrity is the ability of a system to provide timely warnings to users when the system should not be used for navigation [Ref. 9:p. A-3]. A marine navigator must know promptly when a system should no longer be relied upon. This allows a shift to an alternate navigation aid, or may dictate that the vessel be put at anchor until service is restored. Without integrity mechanisms, a temporarily inaccurate system may lead the trusting

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navigator to hazard the vessel. A strong, timely integrity mechanism is a primary requirement of a safe public *radionavigation* service that is usually not critical to a commercial *radiolocation* system, which is intended for positioning.

3. Marine Phases of Navigation

Marine navigation can take place in four areas, or "major phases", as defined by the FRP. The various radionavigation requirements associated with each phase will be delineated in Chapter IV. While some public radionavigation systems can be used in more than one phase of marine navigation, no current system meets the requirements for all. [Ref. 9:pp. 2-3, 2-22, 3-6]

a. *Coastal Phase*

This phase encompasses waters within 50 nautical miles (nm) from shore or within the limit of the Continental Shelf (200 meters in depth), whichever is greater. For an area to be included, there must be a safe path of water at least one mile wide, if a one-way path, or two miles wide, if a two-way path. More restrictive waters are assumed to be in the Harbor/Harbor Approach Phase. The Coastal Phase includes the open waters of the Great Lakes, and any waters where traffic separation schemes have been established, and where requirements for the accuracy of navigation are thereby made more rigid than those of ocean navigation. [Ref. 9:pp. 2-3]

b. *Ocean Phase*

This phase is best described as seaward of the coastal phase just defined. The hazards of shallow water and of collision are comparatively small. [Ref. 9:pp. 2-4]

c. *Harbor/Harbor Approach Phase (HHA)*

This phase usually begins in waters just inshore of those of the coastal phase, normally near the restricted waters of an entrance to a bay, river or harbor. Navigation typically entails transit of a well defined channel which varies from 600 to 120 meters in width. For a seagoing ship entering from the coastal phase, the HHA phase ends at the mooring. [Ref. 9:pp. 2-3]

d. *Inland Waterways Phase*

Navigable channels used by inland traffic are often narrower than the harbor access channels used by large ships. Restricted visibility, shifting of channels in unstable waters, and ice present problems to navigation. Typical traffic includes recreational vessels and tug-barge combinations. [Ref. 9:pp. 2-3]

4. Current Public U.S. Radionavigation Systems

There are a number of radionavigation systems currently in operation which find extensive usage in the civil sector. Each has particular features which make it attractive for certain users. Loran-C, VOR, VOR/DME, TACAN, Transit, radiobeacons, and GPS will be briefly described here; the interested reader should refer to Appendix A of the FRP for further information on these systems, or on Omega, ILS, or MLS.

a. *Loran-C*

This low frequency system was developed to provide a military radionavigation capability with longer range and greater accuracy than its predecessor, Loran-A. It was subsequently selected as the U.S. government-

provided radionavigation system for civil maritime use in U.S. coastal areas. It has also been installed in a number of other areas around the world.

Loran-C is the chief system in use for U.S. coastal maritime radionavigation. However, in order to satisfy the needs of air navigation, Loran-C coverage is now being expanded to fill the present mid-continent coverage gap. The number of land users has increased, largely as part of vehicle tracking/reporting systems. [Ref. 7:p. 1-4]

Loran-C operates at 100 kHz. A typical chain of stations provides reliable ground-wave service over an area 1000 miles across. Within the U.S., Loran-C is maintained by the U.S. Coast Guard and is available more than 99% of the time within the stated coverage areas. Accuracy varies with location within the coverage areas, but absolute accuracy (95%) is specified to be 0.25 nautical mile (nm), but relative and repeatable accuracy is much better, typically 50 to 200 feet. [Ref. 7:p. 1-4]

b. VOR, VOR/DME, TACAN

These three systems provide basic guidance for enroute air navigation in the U.S.; since we are primarily concerned with marine applications, they will only be considered briefly here. Their acronyms have the following meanings: VHF Omni-directional Range (VOR), Distance Measuring Equipment (DME), and Tactical Air Navigation (TACAN). VOR provides bearing with respect to the ground installation, DME provides range, and TACAN provides both (primarily to military users). Since these are line-of-sight systems, ground

coverage is quite limited; however, at 20,000 feet their signals can be received to typically 200 miles. [Ref. 9:pp. A-9 - A-15]

c. *Radiobeacons*

Radiobeacons are nondirectional radio transmitting stations which operate in the low frequency (LF) and medium frequency (MF) bands to provide ground wave signals to a receiver. A radio direction finder (RDF) is used to measure the bearing of the transmitter with respect to the aircraft or vessel. Radiobeacons are relatively inexpensive to install, operate, and maintain; they are widely used throughout the world. [Ref. 9:p. A-19 - A-24]

Radiobeacons operate in three bands: aeronautical non-directional beacons (NDBs), 190-415 and 510-535 kHz.; and maritime radiobeacons, 285-325 kHz. Bearing accuracy is largely dependent on the RDF receiver design and antenna installation, but typical accuracies are about 3 degrees. While coastal coverage is not continuous everywhere, it is sufficient to enable a maritime navigator to obtain frequent lines of position at a low cost. In the U.S., the aviation radiobeacon network provides enough coverage that an aircraft is usually within range of at least one NDB. Radiobeacons will be discussed further in Chapter IV. [Ref. 9:p. A-19 - A-34]

d. *Transit*

Transit is a space-based radiodetermination system that utilizes satellites in approximately 600 nm polar orbits. Users can obtain a fix every one-half to three hours when a single satellite comes into view. Only one satellite is required to get a fix. Transit is operated by the U.S. Navy for worldwide military

use, but there are no barriers to extensive civil use. It is anticipated that operation will be discontinued during the mid 1990s. [Ref. 9: 3-32, A-36]

Transit satellites are typically visible for about 20 minutes, during which time a receiver monitors the doppler effects on the satellite's signals to determine the user's position. For a moving vehicle, accuracy of Transit may be degraded by an erroneous estimate of own course and speed; a 1.0 knot error may cause a 0.2 nm fix error [Ref. 9:p. A-34]. With a single satellite pass using a single frequency receiver, an accuracy of about 500 meters (2drms) is achievable. A dual frequency receiver can correct for ionospheric effects to achieve an accuracy of 25 meters (2drms). [Ref. 7:p. 1-6]

e. NAVSTAR GPS

The NAVSTAR Global Positioning System (GPS) is a satellite-based radionavigation system being developed by the U.S. DOD as a military system with military objectives in mind; it will not be fully available to civilian users. It is a "coarse/fine" system which uses the coarse portion for acquisition and data, and the fine portion for high-accuracy military navigation and positioning. Current policy is to provide the "coarse" Standard Positioning Service (SPS) at a 100 meter (2drms) accuracy level without restriction to the international civilian user community. The policy whereby errors are deliberately incorporated in the system to reduce accuracy to that level is called "Selective Availability" (SA). Military and other authorized users with the correct codes can use the 18 meter (2drms) accuracies of the exclusive Precise Positioning System (PPS). Limitations on civil use are controversial. GPS is described more fully in the next section.

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Differential GPS (DGPS) is an "add-on" to GPS, not a part of the DOD-provided basic system. It uses fixed, ground-based receivers and transmits corrections for GPS inaccuracies in the local area. It allows positioning accurate to under ten meters for all users. DGPS will be discussed in Section C.

The relative accuracies of the some of the ways GPS can be used are summarized and compared with some other radionavigation systems in Table 2-1 [Ref. 9: App. A, Ref. 11:p. 63]. However, predictable accuracy is only a portion of the utility of a system. For example, the superior repeatable accuracy of Loran-C favors that system, while the intermittent availability of Transit detracts from that satellite system's utility.

TABLE 2-1: PREDICTABLE RADIONAVIGATION ACCURACIES (SIGNAL-IN-SPACE) [Ref. 9, Ref. 11:p. 63]

METHOD OF POSITIONING	POSITIONING ACCURACY(2drms)
Loran-C	460 meters
SPS with Selective Avail.	100 meters
SPS w/o Selective Avail.	40 meters
Transit (Dual Freq.)	25 meters
PPS	18 meters
Differential SPS	10 meters

The U.S. Government has recognized the place of GPS in civilian applications in the FRP for years. The Coast Guard has been designated the lead DOT agency for GPS, with responsibility to act as the liaison between civil GPS users and the government. The Coast Guard provides an interface to civil GPS

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users, administers the PPS to qualified civil users, and coordinates input from the Civil GPS Service Interface Committee (CGSIC).

B. GLOBAL POSITIONING SYSTEM

1. Introduction

The Global Positioning System (GPS) is also referred to as NAVSTAR. GPS consists of three segments: *Space* (satellites), *Control* (facilities for remote maintenance and operation of the satellites) and *User* (the receivers). Together, they are designed to provide continuous, three-dimensional navigational fixes anywhere in the world.

GPS should not be confused with the older Transit Navy Navigation Satellite System or with the similar Soviet GLONASS system. GLONASS has much in common with GPS, but uses a different orbital configuration and a different method of distinguishing between individual satellite signals (FDMA instead of CDMA).

2. Space Segment

The complete configuration will consist of 21 fully capable "Block II" model GPS satellites, and three spares. The DOD is expected to declare the GPS constellation fully operational when 21 operational Block II satellites are in place in 1993 [Ref. 9:p. 3-36]. They will be deployed in six circular orbital planes at an altitude of 20,200 km (10,900 nautical miles); this is three satellites plus one spare per plane. The orbital planes will be oriented at about 55 degrees from the equator. This will allow five satellites to be within line-of-sight virtually any time

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and any place. A minimum of four satellites are needed to obtain a full three dimensional point position fix. [Ref. 9:p. A-31]

GPS satellites broadcast continuously to navigational users on two UHF frequencies. Each satellite transmits on the same L band frequencies, L1 (1575.42 MHz) and L2 (1227.6 MHz); however, each employs unique spectrum spreading codes to allow simultaneous transmission by all satellites without interference (code division multiple access). L1 carries a precise (P) code and a coarse-acquisition (C/A, or S) code. L2 carries the P code. The encrypted P-code carries a finer distance measuring scale, and is protected against "spoofing": hostile military transmission of incorrect GPS signals. Also, access to this second frequency allows sophisticated DOD receivers to detect the difference in ionospheric refraction between the carriers, and calculate a correction. All GPS signals are of the spread spectrum type using Bi-Phase Shift Keying (BPSK). The reader seeking a fuller understanding may refer to the clear and concise description of GPS signal modulation and the spread spectrum techniques in *Introduction to NAVSTAR GPS User Equipment* [Ref. 10:p. 1-10].

Each carrier is also modulated with a 50 bits-per-second (bps) navigation data message containing satellite status, time, position, orbital prediction information (ephemeris), a "Hand Over Word" for transition from SPS to PPS modes, and ionospheric delay predictions for SPS users. Parts of this message are encrypted for military use.

3. Control Segment

This segment is made up of one Master Control Station at Falcon Air Force Base (Colorado Springs, Colorado) and four monitor stations around the world. The monitor stations collect satellite ranging and timing data, which is passed to the Master Control Station for processing. The resulting satellite orbital position and clock error information is sent to a ground antenna site for upload to the satellite for later retransmission to its users. The Master is also responsible for controlling orbital corrections.

4. User Segment.

There are many makes and models of receivers available for various applications: military or civilian; navigation, differential reference station, surveying or time transfer; single- or dual-frequency; hand-held or vehicle mounted, and many others. The following will be a very brief overview of this segment of the GPS. The reader seeking a fuller understanding may refer to the excellent description of the generic GPS receiver in Langley's "The GPS Receiver: An Introduction" [Ref. 12:p. 50-53].

a. Receiver Components

User equipment may be broken down into the following conceptual components:

- Antenna and Associated Preamplifier: convert electromagnetic energy into electric current over the desired frequency range.

- Radio Frequency (RF) front end section: translate the L-band signals down to a lower intermediate frequency (IF) more easily processed in the rest of the receiver.

- Signal Tracker: Isolate the signals from each satellite in order to allow the receiver to measure their pseudoranges. This signal processing function will be discussed in the following subsections.

- Microprocessor-Controller: performs overall operation of the receiver and navigation processing of the pseudoranges.

- Command Entry and Display Unit: the keypad and display screen. In some units, a separate computer provides this function through a data port on the receiver.

- Power Supply

b. Receiver Principles

The GPS receiver determines the time of arrival of each satellite signal by synchronizing an internal signal having that satellite's code with the satellite's received signal. This is called code-tracking. Each satellite gives its exact time and position of transmission. The receiver measures the time of reception to compute travel time as "pseudo-ranges"; these are not true ranges, because of the receiver clock time bias error included in them. Pseudoranges from four or more satellites enable the GPS receiver to determine position and time. Essentially, the receiver solves for four unknowns (three dimensions and time) with four known satellites. and ultimately position, velocity, and precise time.

In addition to the code-tracking measurement, it is also possible to phase-lock onto the carrier. Carrier measurements can be used to directly calculate velocity as well as improve position estimates.

c. Receiver Designs

Signal tracking techniques can be grouped into three different approaches: multi-channel parallel, multiplexed, and sequential designs. In the multi-channel parallel design, one channel is dedicated to tracking the signal of

one satellite. This gives the best performance, but costs the most. In the multiplex design, each satellite signal is sampled in turn, very rapidly. This design has the multi-channel feature of "continuous" tracking, but at a reduced signal-to-noise ratio. In the sequential design, the receiver dwells for a short time on each satellite. The receiver goes through a "mini-reacquisition" of each satellite during each cycle (which is typically 2 to 5 seconds long).

Recent advances in digital technology are making multi-channel parallel "all-satellites-in-view" receivers increasingly cost-effective. A technique referred to as *baseband processing* uses one RF (analog) channel to down-convert and digitize the IF signal; code and carrier tracking is subsequently performed digitally with software on many discrete channels. Since the samples are taken (i.e., analog to digital conversion performed) prior to correlation, no further analog circuitry is required for any number of simultaneous tracking channels.

5. Navigational Geometry

Given two position lines to establish one's position in any navigation problem, it is best if they cross at right angles. The certainty of the position degrades if the angle becomes smaller, until total confusion results with parallel lines. The measure used to quantify this factor in the uncertainty of a fix is Dilution Of Precision (DOP). In the Horizontal plane it is called HDOP, and in three dimensions it is called Position DOP, or PDOP. Generally speaking, the smaller the DOP value the more precise the position. [Ref. 10:p. 3-7]

The ideal geometry for a GPS three dimensional fix with four satellites in view is: one directly overhead, and three equally spaced about the horizon, just

above the horizon "masking angle". The volume of the tetrahedron thus formed is a good indicator of the merit of the fix geometry [Ref. 13]. Situations may arise where the satellite geometry degrades so badly that no reliable position may be determined, even though the satellites and the user equipment are operating perfectly.

6. GPS Integrity

A GPS receiver typically utilizes health and navigation information transmitted by satellites, as well as its own satellite geometry algorithms to estimate the overall merit. Some satellite health indicators and operating parameters are monitored within the satellite, and users may be notified of detectable internal failures within six seconds. For more subtle failures, GPS satellites are monitored more than 95% of the time by the control segment monitoring stations. If a problem is detected, the Master Control Station will change the satellite's navigation message at the next opportunity; unfortunately, this may take from 15 minutes to several hours [Ref. 9:p. A-35]. This is the major weakness in the GPS system, especially in the eyes of the aviation community. One beneficial effect of DGPS service is the provision of this integrity information over its area of coverage. Three other alternatives are discussed below: RAIM, use of existing radionavigation transmissions, and a GPS Integrity Channel.

a. RAIM

Receiver Autonomous Integrity Monitoring (RAIM) is a method of incorporating any available redundant satellite pseudoranges in an algorithm to check whether one seems to be transmitting unreasonable information. This is

only possible when satellite geometry is favorable. When 24 satellites are operational, RAIM should detect a failure over 99.97% of the time. However, if only 21 are left in the constellation (no spares), an additional failure will only be detectable about 95% of the time (conservative estimates) [Ref. 14:p. 46].

b. *Existing Radionavigation Transmissions*

A variation using RAIM has been incorporated in user equipment sets that utilize another navigation system [Ref. 14:p. 44-48]. *Hybrid* user sets that combine pseudoranges from both GPS satellites and Soviet GLONASS are technically feasible. Their use would increase accuracy (improved DOPs), availability and integrity. Failures at any transmission source would be detectable using RAIM algorithms. The proposal to integrate GPS and Loran-C pseudoranges in one user set to improve availability and integrity follows the same concept, particularly if Loran-C transmitters were synchronized to GPS time [Ref. 15:pp. 95-109].

c. *GPS Integrity Channel*

The aviation community is especially interested in making GPS integrity information available over wide areas. A suitable system for aviation applications must be capable of alarming within ten seconds of a failure, have very high availability, and should minimize false alarms [Ref. 16:pp. 27-28]. Implementing the GPS Integrity Channel (GIC) concept would accomplish this.

> The FAA is presently planning to implement a GIC network to provide a GPS integrity service covering most of North America. [In 1991] the agency will publish a request for proposals for a GIC system, with acquisition of system components scheduled for 1994 and implementation in 1996.... However, the cost of developing and operating a GIC may prohibit its implementation. [Ref. 14:p. 45]

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It would appear that Inmarsat is developing just this type of capability in its third generation communications satellites. In August 1990 Inmarsat demonstrated a prototype system that generated a spread spectrum signal on the ground, relayed it through a frequency-shifting geostationary satellite, and received the necessary "GPS look-alike" information on the ground. The idea is to rapidly transmit information on any failing satellites in the format of a navigation message that can be handled by a slightly modified GPS receiver. Eventually, it may also be possible for the precision of time and ephemeris to be improved to where the GIC communications satellite could also be used for an additional pseudorange [Ref. 17:p.91]. In November 1990 the Inmarsat Council approved the inclusion of a navigation repeater on board third generation Inmarsat satellites. This is intended to permit interested agencies (e.g., the FAA and the European CNES) to have a functioning GIC in place when GPS becomes fully operational. [Ref. 18:pp. 35-36]

7.   **Time**

The result of every SPS fix is the synchronization of the receiver's clock with those in the GPS satellites to within 167 nanoseconds (one sigma) [Ref. 9:p. A-32]. Using two receivers to accomplish this time transfer improves the result by another factor of ten; this makes GPS based time transfer the most accurate method available for synchronizing clocks between the national standards laboratories [Ref. 11:p. 63].

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C. DIFFERENTIAL GPS

Differential operation of GPS potentially offers accuracies of 2 to 10 meters for dynamic navigation applications and better than 2 meters for stationary applications [Ref. 7:p. 1-8]. The basic concept of differential GPS is similar to that which has also been successfully employed to improve the accuracy of Loran-C, Omega, and Transit. In addition, differential operation would effectively serve as a GPS integrity monitor, alerting the user whenever a particular satellite pseudorange was so far out of tolerance as to be unusable, even with a differential correction.

1. Description of the Technique

A GPS reference receiver is placed at a surveyed location. By comparing the known satellite range with measured ranges produced by GPS (using SPS), corrections to each satellite's pseudorange can be determined. These corrections can then be broadcast to nearby DGPS equipment sets, which use them to improve their range measurements. [Ref. 7:p. 1-11]

The differential technique corrects pseudorange bias errors due to causes outside the user equipment. In the case of GPS, the major sources of error are the following [Ref. 7:p. 1-9]:

- Ionospheric delays: signal propagation group delay, which can be as much as 20 to 30 meters during the day and 3 to 6 meters at night. In the two-frequency mode of operation of the PPS, this effect is largely removed by applying the inverse square-law dependence of delay on frequency.

- Tropospheric delays: signal propagation delays caused by the lower atmosphere. While the delays are as much as 30 meters at low satellite elevation angles, they are quite consistent and can be modeled. Variations in the index of refraction can cause differences (between reference station and user) in signal delays of 1 to 3 meters for satellites at low elevation angles.

- Ephemeris error: differences between the actual satellite location and the location predicted by the satellite orbital data. Normally these are less than 3 meters.

- Satellite clock errors: differences between the satellite clock time and that predicted by the satellite data. The oscillator that times the satellite signal is free-running. The GPS ground control system monitors clock drift. Clock drift information is provided to the GPS receiver through the use of satellite navigation data. The GPS receiver decodes the data and adjusts the signal timing accordingly.

- Selective Availability errors: the above-described errors in the ephemeris and satellite clock are increased at each satellite for security reasons. GPS PPS users have access to information on these errors and can eliminate them entirely.

Consistent satellite clock errors are corrected by differential operation, as long as both the reference and user receivers are using the same satellite data. Ephemeris errors, unless they are very large (30 meters or more), are similarly compensated by differential operation. Selective availability errors affecting the timing of the signals are compensated by differential operation in the short term, but the corrections lose their validity over time. For users near the reference station, the respective signal paths to the satellites are sufficiently close so that ionospheric and tropospheric compensation is almost complete. However, as the user to reference station separation is increased, the different paths to the satellites may be sufficiently different that the atmospheric variations cause the delays to differ significantly. This results in an error that will be greater at larger user to reference station separations and time delays. [Ref. 7:p. 1-8,9]

Thus, the baseline distance between the differential reference station and the user, and the age of a correction when it is applied to the measured pseudorange by the user are the DGPS service design factors that degrade the

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accuracy of the user's solution. They result in "spatial decorrelation errors" and "time decorrelation errors", respectively.

These effects are illustrated graphically in Figures 2-1, 2-2, and 2-3 [Ref. 19]. The impact of time delay on one pseudorange may be seen in Figure 2-1; the graph shows predicted pseudorange error and actual pseudorange error observations on two different days in 1989 while Satellite #14 appeared to be under the influence of selective availability. This is discussed in detail in a 1990 Institute of Navigation paper [Ref. 20]. The estimated effect of distance is shown on Figure 2-2. The precise numbers on the three dimensional graph of Figure 2-3 depend on many other factors, including the presence of selective availability and the satellite geometry at the moment.

2.   Description of Components

Terminology used to describe the necessary functional parts of a DGPS service varies in the published literature. As discussed in Chapter IV, there are many possible ways the DGPS corrections could be transmitted. There are also a wide variety of configurations that could be adopted to implement DGPS Service by any given type of transmitter, as is discussed in paragraph 3. Furthermore, the technology is undergoing rapid change. For these reasons, the components of DGPS service will be discussed only in very general terms; the referenced sources contain more specific implementation details.

In this thesis, DGPS is discussed in terms of five basic, functional components: a differential reference station, a broadcast node, network communications, a broadcast integrity monitor, and user equipment. These
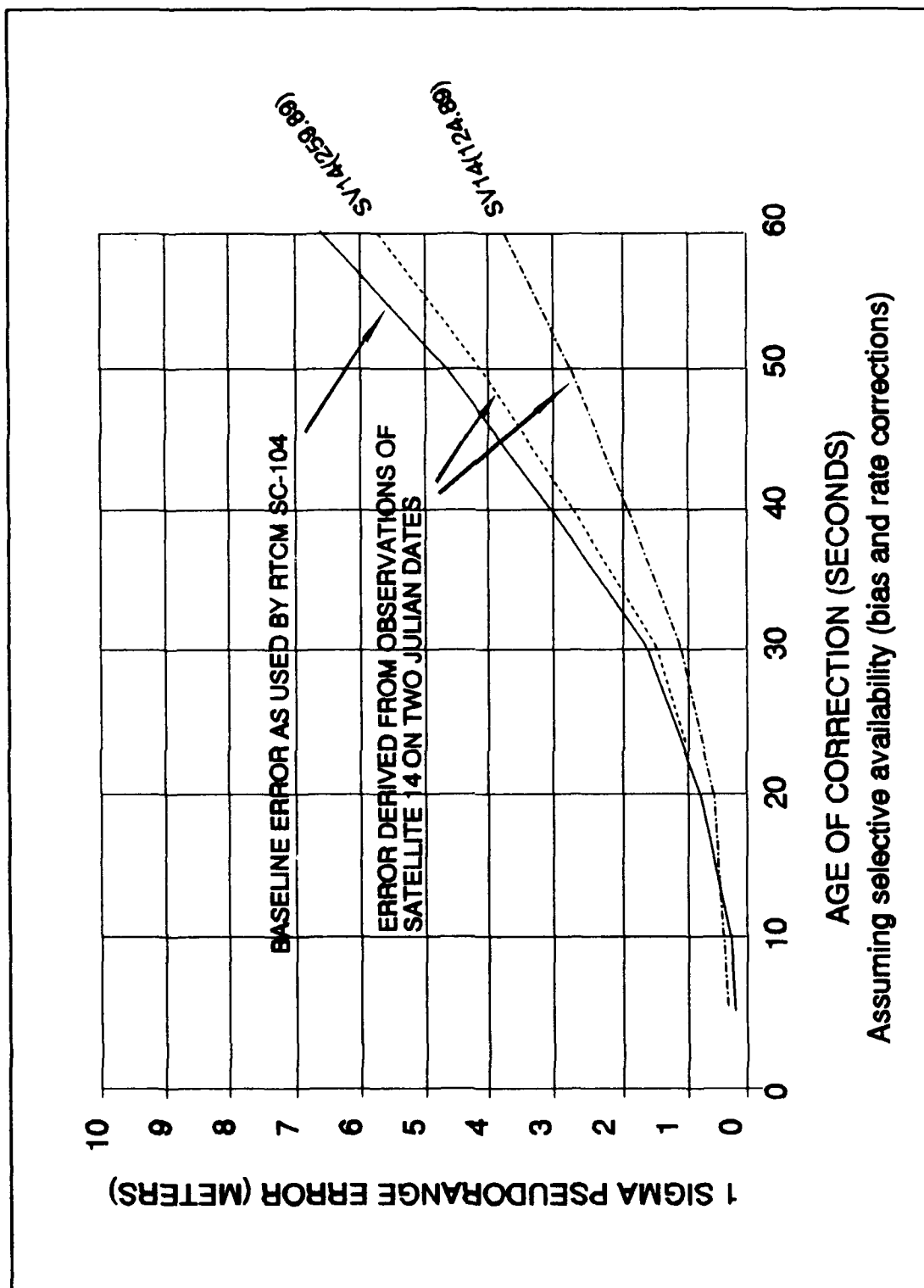
Figure 2-1. Growth of Pseudorange Error with Age of Correction [after Ref. 19]
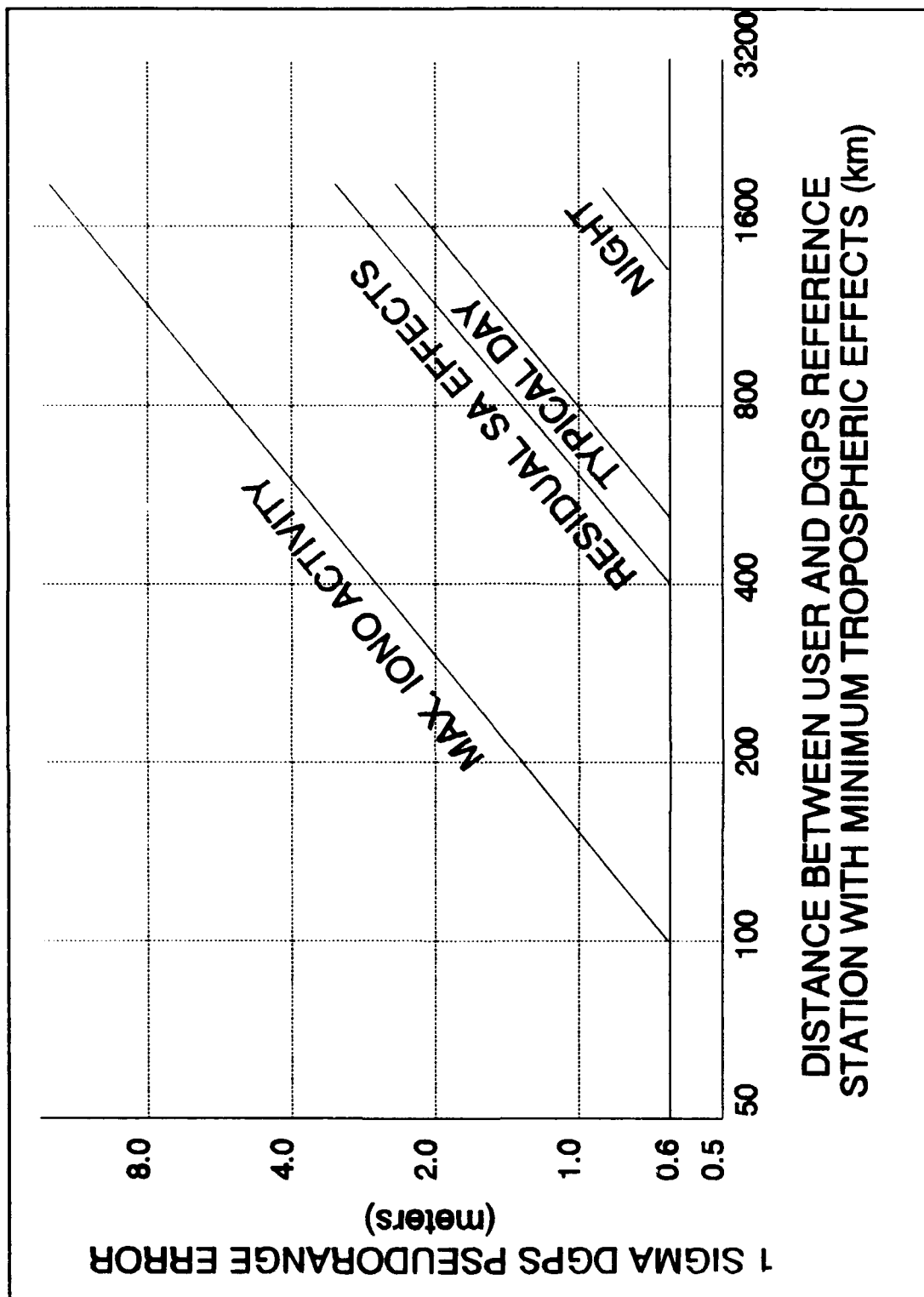
Figure 2-2. Growth of Pseudorange Error with Distance
[After Ref. 19: Taken from G. Nard, Sercel]

Figure 2-3. DGPS Coverage Cube [After Ref. 19]

conceptual components might be physically grouped in many different ways, but in general, they interact as illustrated in figure 2-4. This shows a terrestrial broadcast node. However, a satellite-based system would relay the signal through a geostationary satellite above the GPS constellation (not shown). System control and integrity monitor location are design dependent and may vary from that shown in Figure 2-4. The information flow may be simplistically tracked through a properly functioning system as follows:

- The GPS SPS satellite signal is received at the differential reference station. A pseudorange correction is determined by finding the adjustment necessary to bring the observed pseudorange into agreement with the surveyed reference station position.

- The correction is passed through network communications to the broadcast node.

- The broadcast node transmits the correction information on the appropriate radio frequency (e.g., radiobeacon MF or satellite UHF).

- The broadcast integrity monitor within the broadcast coverage area receives the correction information and checks its integrity. A report of satisfactory operation is made via network communications.

- A user within the coverage area receives the correction through DGPS broadcast receiving equipment, turns off its normal GPS ionospheric and tropospheric corrections, and applies the DGPS information to pseudoranges received directly from the GPS satellites.

a. Differential Reference Station

This component contains a GPS antenna and receiver, a data processor, a data formatter and an interface to the network communications link [Ref. 7:p. 3-2]. The GPS receiver monitors the error in the received signal from each GPS satellite in view, and generates pseudoranges. The data processor uses the station's known position coordinates to determine the corrections. The data

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Figure 2-4. Conceptual DGPS Components

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formatter incorporates these into the RTCM SC-104 message form. Other functions performed here may include the first level of DGPS integrity monitoring (using an independent GPS receiver) and data logging. The differential reference station may be locally or remotely controlled [Ref. 21:p. 8].

The RTCM supports the use of a high-quality atomic clock with a differential reference station [Ref. 7:p. 3-6]. Its precise time measurements allow more exact tracking of the GPS signals. This precise time is also needed to maintain consistent clock bias in the transmission of RTCM "Message Type 9" (rapidly changing DGPS corrections). However, the issue is not decided, and research continues in regard to this requirement:

> With the current new reference receiver hardware supplying regular GPS carrier data on all channels, these new filter designs can operate on crystal clocks and achieve accuracy equivalent to that of a reference station driven by a rubidium frequency standard. [Ref. 22:p. 187]

b. *Network Communications*

The data to be broadcast are transformed into a data stream suitable for intra-system communication. For example, this link might be a dedicated commercial telephone line or a microwave radio link between the differential reference station and the broadcast node. Both the control of this circuit and the coding of the data are distinct from the functions of the differential reference station. [Ref. 21:p. 8]

c. *Broadcast Node*

The corrections (structured according to the RTCM SC-104 format) are transformed into radio signals that can be received by mobile users in the coverage area. The description of the signal transmitted from the broadcast node

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(the "broadcast service standard") is not laid out by the RTCM recommendations, but will be important information for equipment manufacturers and users once defined [Ref. 21:p. 8]. The RTCM describes this function as follows:

> In its simplest form the data link continuously carries the differential GPS data message without interruption, at a constant data rate of at least 50 baud.... However, it is of no concern to the receiver whether the data is transmitted continuously or in bursts, or whether protocol overhead is added. For example, ... preamble, parity, and even error correction bits [could be added before transmission and] stripped off at the receiver end, and the differential correction bits would be stored in the buffer, to be transferred to the receiver at will.
>
> Differential GPS broadcasts intended for general public use would require that the data link be a standard, published design. For non-public use, however, the reference station, data link, and receivers could be part of an integrated differential GPS system. In such a case, the data might be encrypted to limit the service to paying customers. [Ref. 7:p. 3-9]

d. Broadcast Integrity Monitor

This is equipment that monitors the DGPS service broadcasts and GPS signals to determine the level of performance being provided. This information is used to control the operation of the DGPS service and guarantee that the advertised level of performance is being maintained. It performs the second level of DGPS Service integrity monitoring, assuming that the first level was performed at the differential reference station. [Ref. 21:p. 9]

Since the differential reference station is broadcasting messages on all satellites in view, the broadcast integrity monitor can not be an ordinary user equipment set monitoring its own position [Ref. 23:p. 3]. It has to check to ensure that each pseudorange correction obtained from the broadcast does not differ more than a specified amount from its own observations; if it does, an alarm is generated. When all components are functioning properly, the broadcast integrity

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monitor will provide frequent (perhaps continuous) feedback to the differential reference station.

The broadcast integrity monitor is really performing two services:

- It checks the validity of the corrections generated by the reference station and modulated onto the broadcast. For this purpose, the monitor need only be far enough away from the reference station to ensure its GPS antenna is in a different multi-path environment.

- It checks the strength of the broadcast signal. For this purpose, the monitor must be at least far enough away from the broadcast node to avoid being overpowered by the transmission. At least one integrity monitor is required per broadcast, regardless of the number of differential reference stations per broadcast node.

The site optimally placed for one function may be far removed from the optimal location for the other. The differential reference station to broadcast node ratio will be significant in determining how many integrity monitors of what type are required. Hereafter, this study simplifies discussion by assuming that there is one integrity monitor per reference station, though this need not be the case with some configurations (e.g., dedicated satellite channel, VHF/FM channel).

e. User Equipment

This component consists of two subparts: the broadcast receiver and the GPS/DGPS navigation set. The broadcast receiver could be a satellite terminal or a radiobeacon broadcast receiver, for example. The navigation set receives the GPS signals directly from the GPS satellites and accurately processes them; it then applies the DGPS corrections from the broadcast receiver for an improved solution.

At this time, user equipment fully capable of RTCM SC-104 differential operation is limited. However, differential capability is being incorporated as a software addition to an increasing number of GPS navigation

sets. While DGPS capability is now a justification for a significant price mark-up, addition of DGPS requires no extra hardware in the navigation set [Ref. 24]. Therefore, it is reasonable to expect that with time and increased competition, the incremental cost of DGPS-capability over GPS-only capability will be due to the broadcast receiver.

3. System Architecture

The focus of the cost-effectiveness analysis in Chapter V compares two systems that differ only with respect to the type of broadcast node; otherwise, they are assumed to use equivalent system architectures. However, the problem of optimizing the configuration of other system components *could* be approached using the model presented in Chapter V. The following paragraphs touch on some of the technical issues involved.

As previously mentioned, there are a wide variety of configurations that could be adopted to implement DGPS Service by a given type of transmitter. Some of these variations blur the distinction between the components. For example, in the above discussions, conversion of the differential corrections into RTCM message formats and any necessary interleaving takes place at the differential reference station; these tasks could also be performed at the broadcast node.

Whatever broadcast method is selected, a major design task will be evaluation of the need for incorporation of a control station. Under this concept, the service provider (Coast Guard) would exercise quality control over subordinate components from a central location. This would include controlling and monitoring the health of the subordinate components and network communications. This

centralized scheme would require development of a complex hardware and software system, which increases cost and the risk of the project running over schedule. However, the centralized scheme has several advantages, and they are [Ref. 25]:

a. *Availability*

Assuming reliable, redundant communications links, the centralized scheme should result in better availability. It would facilitate identification of the point of failure in the event of contradictory component health indications. The faulty component alone could be declared unusable, rather than the whole system.

b. *Portability*

A control station architecture would facilitate the central collection of information from all components for forwarding to many broadcast media. The information might also be more readily archived or forwarded to other users for post-processing.

c. *Technical Flexibility*

It would facilitate future system improvements more readily than an autonomous approach. In many cases, this might require only a software change at the control station [Ref. 26]. This concept would consolidate the processing of satellite error information from several reference receivers at a central facility, and could permit "extrapolated" multi-receiver solutions for improved accuracy. Conceivably, meteorological information could be added. Potentially fewer reference receivers would be required in this architecture than in the autonomous approach illustrated above. After this central processing, the RTCM messages would be forwarded to the broadcast nodes. Once established,

such a Wide Area Reference Station (WARS) could be assigned additional GPS related tasks [Ref. 27].

d. Synergy

This architecture could allow integration with the control mechanisms of other Coast Guard systems, for an overall synergistic effect. Many types of resource cross- utilization might be possible. The sharing of network communications links is the most obvious of these. For another example, the same type of cesium atomic time standards used by Loran-C stations could be utilized by DGPS reference receivers. Manpower efficiencies could be had by combining routine watchstander responsibilities.

e. Security

A manned control station would facilitate immediate, centralized control in the event service must be interrupted in the interest of national security. This is discussed further in Chapter III.

4. RTCM SC-104 Recommended Standard

The Radio Technical Commission for Maritime services Special Committee 104, (RTCM SC-104), Differential NAVSTAR/GPS Service, examined the technical and institutional issues surrounding DGPS services, and published the following version 2.0 recommendations [Ref.7:p.1-1]:

- Data Message and Format: The message elements that make up the corrections, the status messages, the station parameters, and other data are defined. They are structured into a data format similar to that of the GPS satellite signals, but a variable-length format is employed. These messages have different levels of finality. Some message types have been "frozen" (i.e., they will not be subject to change) and other message types are considered tentative; see Table 2-2.

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- User Interface: A standard interface is defined which enables DGPS user equipment to be used in concert with a variety of different data links. This enables, for example, DGPS user equipment to be used with a satellite or a radiobeacon data link.

- Pseudolite Design - A particular embodiment of a differential station is the "Pseudolite", which looks to the user like an extra satellite and obviates the need for a separate data link for the broadcast of corrections. A design is proposed which appears to overcome the interface problems associated with conventional techniques.

The Committee has attempted to address the needs of a wide user community, including not only marine users but land-based and airborne users. Both radiolocation and radionavigation applications are supported. A standard data link interface is defined which will enable a receiver to utilize different data links to receive corrections. [Ref. 7:pp. 1-2, 4-5]

Message types 60-63 have been reserved specifically at the request of the Coast Guard to explore the use of multi-purpose data links. If radiobeacons come into operational data link use, the Coast Guard would like to be able to use them for more than DGPS data. This general format could be used to transmit differential Loran-C, differential Omega, weather messages, or *Notices to Mariners*. [Ref. 7:p. 4-32]

Frequent updates using "Message Type 1" is a key factor in determining the accuracy of a RTCM-compatible system; this provides the pseudorange correction and the rate of change of that correction. These values are used by the user equipment at time of receipt to differentially correct its own measured GPS pseudorange. Since its value degrades with time, it is important to maximize the rate of transmission of the Type 1 messages. Estimations of that rate of transmission are detailed by the RTCM recommended standards document. These

estimates assume the minimum 50 bps data rate with selective availability in effect, and account for interleaving of other message types as necessary. The more satellites in view, the longer the time between updates of any one satellite [Ref. 7:p. 4-33]:

- Four Satellites: repeat Type 1 Message every 6.67 sec.

- Seven Satellites: repeat Type 1 Message every 11.11 sec.

- Eleven Satellites: repeat Type 1 Message every 18.18 sec.

TABLE 2-2: MESSAGE TYPES DEFINED BY RTCM SC-104
[Ref. 7;p. 4-5]

Message Type #	Current Status	Title
1	Fixed	Differential GPS Corrections
2	Fixed	Delta DGPS Corrections
3	Fixed	Reference Sta. Parameters
4	Tentative	Surveying
5	Tentative	Constellation Health
6	Fixed	Null Frame
7	Tentative	Radiobeacon Almanacs
8	Tentative	Pseudolite Almanacs
9	Fixed	High Rate DGPS Corrections
10	Reserved	P-Code DGPS Corrections (all)
11	Reserved	C/A-Code L1,L2 Delta Corr'ns
12	Reserved	Pseudolite Sta. Parameters
13	Tentative	Ground Transmitter Parameters
14	Reserved	Surveying Auxiliary Message
15	Reserved	Ionosphere (Troposphere) Msg.
16	Fixed	Special Message
17	Tentative	Ephemeris Almanac
18-59	--	Undefined
60-63	Reserved	Differential Loran-C Messages

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III. NATURE OF THE PROBLEM

Without a well-considered foundation of objectives and assumptions, the
effort expended in Cost-Effectiveness Analysis (CEA) may be wasted. It may
recommend a system not suited to the problem. The objectives in this chapter lay
the foundation for determining the criteria by which effectiveness will be
measured. The assumptions and considerations documented in Section B continue
this explanation by addressing several issues pertinent to DGPS service design.

A. OBJECTIVES

This section addresses the process of setting objectives, then discusses each
tentative objective associated with the following "missions":

- Harbor and Harbor Approach Radionavigation

- Coastal Phase Radionavigation

- Coast Guard Cutter Precise Positioning

- Vessel Traffic Control

- Precise Air Navigation

- Support of Other Agencies' DGPS Missions

- Support of Other Radionavigation Services

1. Definitions

The meanings of "objective" and "requirement" vary in the referenced
sources. For the purpose of this study, the noun "objective" means a general goal,
usually stated in terms of a capability to perform a mission: harbor radionavigation

capability, for example. Objectives drive "requirements". System requirements more specifically define what level of performance must be provided by a proposed system to bridge the gap between what is possible now and a desired objective; for example, ten meter (2drms) accuracy with 99.9% reliability might be a requirement driven by the Harbor Radionavigation objective. System requirements should quantify *what* level of performance should be achieved rather than *how* it should be achieved.

2. Process of Defining Objectives

Acquisition policy and systems engineering texts are unanimous in stressing the importance of user input and organizational agreement on objectives. Without this, a project is more likely to be diverted or cut completely in mid-course, or to produce the wrong system. Objectives are often hard to formulate, however. In the public sector, both external demand and internal support inputs are diffused through the complex policy making structure of the government. Participating institutions include the Congress, the president and the executive agencies, and the general public and special interest groups. [Ref. 5:p. 29]

a. Incremental Decision Making

For a federal agency such as the Coast Guard, objective setting is complicated by the gradual nature of decision making in the public sector. The perceived needs of the country are constantly changing with the time, as discussed in Chapter I.C.3. This means that detailed objective setting efforts may be wasted if attempted with too much rigor. In *Managing a Federal Agency*, Bragaw discusses how incrementalism affects Coast Guard policy making:

... a federal agency makes a decision and then adapts or adjusts the decision in response to the forces it experiences after the first decision is made. The discussion of the "issue-attention" cycle...points out that many of the issues an agency deals with go through a cycle of relative importance, and decisions made by a group or an agency fluctuate with this cycle. The proponents of incrementalism point out that, although the process can be termed "muddling through" when looked at from a distance, it may actually be quite responsive to the democratic system of government.... One should avoid the idea that many Coast Guard decisions were made as part of a profound national policy. The evidence...strongly indicates that decisions made at any one point in time are products of the forces at work at that moment....This is not to say that the concept of an incremental decision-making process is wrong. Quite the contrary--an idea may develop and progress until it becomes an element of national policy. This development does not necessarily occur, however, because any group or committee plans it or says it will happen this way.... [Ref. 5:pp. 43, 235-236]

b. *User Demand*

In high-technology endeavors, the users often don't know what they want until they get it. What comes first, the system or the requirement? In the case of GPS, the Coast Guard radionavigation user survey completed in January 1989 indicated that two thirds of recreational and small commercial vessel operators had no knowledge or experience with GPS; only 3% had actually used it [Ref. 28:p. 23]. Considering that GPS is scheduled to be fully operational in 1993, the problem is particularly acute. A tradeoff exists between the risk of underestimating capabilities that the user community will come to want and over-designing capabilities for which no demand will develop [Ref. 29]. Until a prototype is available, even the designers, familiar with system potential, are merely guessing what applications an unprecedented capability will lead to. A historical example is the use of Loran-C with automated dependent surveillance to track cargo movements:

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Technological change usually brings forth new applications that transcend the need for which an innovation was first developed, but such new applications often raise managerial objections because they go beyond the area the organization serves. This certainly happened in Loran-C; a user constituency developed that was much larger than the original group of mariners and aviators. Transportation and inventory control of goods as they are shipped by one transportation mode then shifted to other modes until they reach the final distribution centers are huge potential applications. There are many others, made technically possible by miniaturized receivers that can be interrogated to "send back" their position at any time. [Ref. 5:pp. 146-147]

c. *Technological Uncertainty*

Just as a future change in technology may increase demand for services, it may also lead to the project being overtaken by events. Despite in-depth analysis from the start, unexpected technological advances may dictate limited fielding or abortion of the program altogether. An example (in the case of DGPS) would be drastic improvements in unaided GPS system accuracy and integrity from satellite and receiver technological advances, combined with a change in national policy to make such precision available to the public. If PPS were to be released for public use, and an integrity channel were available, the need for DGPS at all would deserve revaluation.

d. *Plan for Incremental Growth*

A key to managing a project such as DGPS under such dynamic conditions is to have a flexible plan that will adapt to changing objectives as time progresses. The project plan should be modular, so as to allow implementation in increments; such adaptability improves the project's budget survivability [Ref. 30]. Modular design also facilitates preplanned product improvement; this will be considered further in section B.6.

3. DGPS Objectives Listing

Why is a DGPS system needed in the first place? The Coast Guard has addressed the possible objectives by proposing applications in planning and budgeting documents, including the DGPS Tentative Operational Requirement (TOR) [Ref. 31], various G-N Issue Memoranda on DGPS, a Resource Change Proposal (RCP) [Ref. 3], and the 1990 Federal Radionavigation Plan (FRP) [Ref. 9]. These plans are changing continually. Additional objectives outside these sources are not addressed, although there are many in the referenced literature; for example, neither radionavigation on the inland waterways nor the 13 militarily oriented applications itemized in a NATO guide to GP$^{\cdot}$ [Ref. 10: p. 11-4] will be analyzed. However, the discussion after each of the following general objectives includes the author's observations.

a. *Harbor and Harbor Approach (HHA) Radionavigation*

DGPS service has the potential to meet the accuracy, reliability and integrity needed in this phase, as outlined in Chapter II and in the FRP [Ref. 9:p. 2-3].

There was not a strong demand for DGPS level accuracy expressed by the maritime public as of 1989; most navigators find existing systems, such as Loran-C, adequate for their needs [Ref. 28:pp. 24,45,46,79]. However, the previous discussion of Section 2.b applies: users don't really understand the utility of the increased capability until it is available. The marketing of products that apply DGPS will increase demand. In particular, the technology of electronic display systems is complementary with DGPS-level accuracy and fix-interval:

It would appear that a major step in maximizing the effectiveness of radionavigation systems in the harbor/harbor approach environment is to present the position information on some form of electronic display. This would provide a ship's captain, pilot, or navigator a continual reference, as opposed to plotting "outdated" fixes on a chart to show the recent past. It is also recognized that the role of the existing radionavigation system decreases in this harbor/harbor approach environment, while the role of visual aids and radar escalates....a user must be able to relate the data to immediate positioning needs. This is not practical if one attempts to plot fixes on a chart in the traditional way. To utilize radionavigation information that is presented at 6- to 10-second intervals on a moving vessel, some form of an automatic display is required. Technology is available which presents radionavigation information along with other data. [Ref. 9:pp. 2-26]

DGPS potentially offers the user a trade-off between safety and economic efficiency. On one hand, HHA DGPS service should enhance maritime safety by reducing the number of ship groundings, especially those due to human error (e.g., confusion when operating in unfamiliar waters at night). Alternatively, a vessel could use DGPS to reduce time and fuel expenditures by taking the fastest route, rather than "going around" to a safer channel, or waiting for favorable conditions (optimal tide or current state, improved visibility, or reduced traffic congestion). There is a tremendous risk of accident if a vessel master accepts this finer margin of error, but loses DGPS or the electronic display system and is forced to immediately shift to visual navigation by buoys.

If vessels use DGPS to enhance safe operation, the threat to the environment from spilled oil or other hazardous materials would be reduced. A shiphandling simulator experiment conducted in 1988 supports this contention. A simulated ten meter (2drms) accuracy on a graphical electronic display in visibilities as low as 0.25 nautical mile allowed commercial vessel pilots to perform as good as or better than they had performed when visually piloting in unrestricted visibility [Ref. 4:p. 325]. However, the same evaluation of 18 meter accuracy

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resulted in statistically poorer performance than visual piloting, most significantly so in turns [Ref. 32:p. 20].

The TOR mentions the potential of DGPS to have integrity sufficient to allow "sole means" use; this is a term typically used in aviation navigation literature that implies a very high degree of dependability. However, it should not be construed to rescind the venerable "prudent mariner" caveat (printed in the margins of nautical charts) against relying solely on any single aid to navigation [Ref. 33:p. 1]. Under this caveat, DGPS could provide "primary means" with other sources (such as visual aids, radar, and fathometer) acting as checks as appropriate. Indeed, if "sole-means" were to imply safe navigation in the absence of visual aids in zero visibility, the 1988 simulator experiment indicates that DGPS level accuracy (10m, 2drms) may not be adequate to the task:

> The experimental results do not support the use of the types of radio aid systems evaluated during this experiment as a principal means of navigation under zero visibility conditions. The primary concerns focus on the need for (a) additional research into the role of an RA [Radio Aid] device in negotiating turns under zero visibility conditions and (b) additional insight into the minimum training requirements for using such devices. [Ref. 32:p. 30]

b.   *Coastal Phase Radionavigation*

Early planning calls for DGPS coverage to extend 20 kilometers seaward from each critical U.S. waterway [Ref. 31]. This would include the coastal areas of the continental U.S., Alaska, Hawaii and Puerto Rico. However, the remote areas of Alaska and Hawaii, where maritime commerce is quite infrequent, and the navigable rivers may not be covered [Ref. 3:p. 2]. The FRP specifies that in the "coastal phase" outward of harbor approaches the ship will be provided with

a safe path of water at least one mile wide [Ref. 9:p. 2-3]. This is not a particularly demanding environment in comparison to the HHA phase just discussed, and the existing GPS and Loran-C coverage would seem very adequate for safe navigation. However, the 20 kilometer swath does give a comfortable transition zone wherein the inbound navigator may verify reception of a DGPS signal and proper operation of the ship's receiver.

It does not appear that DGPS would provide much additional utility over unaided GPS beyond the Coastal Phase. The FRP specifies that 100 meter accuracy is more than adequate for safe navigation in the Ocean Phase. One rationale for extending coverage further than 20 kilometers out would be to have DGPS provide integrity information for the GPS system, notifying users when a satellite is unusable. However, it is likely that hybrid Loran-C/GPS receivers, a geostationary satellite GPS integrity channel, or Receiver Autonomous Integrity Monitoring (RAIM) will eventually provide this function, as discussed in Chapter II, Section B.

c. *Coast Guard Cutter Precise Positioning*

DGPS accuracy is considerably above that available with unaided GPS; this precision is desired for improved effectiveness and productivity in performing Coast Guard duties, such as buoy positioning. The coverage, integrity and reliability required in all these missions are generally less demanding than those just discussed for HHA Radionavigation, while required accuracy is roughly the same.

(1)   *Aids to Navigation.* The USCG Research and Development Center (R&D Center) at Groton, CT, has already deployed prototype DGPS technology for evaluation in buoy positioning. The stated accuracy goal for this mission is five to ten meters (2drms) [Ref. 21:p. 13]. Operational demonstrations have proven the potential of DGPS to replace horizontal sextant angles as the primary means of positioning buoys.

The Automated Aid Positioning System (AAPS) is a laptop computer-based tool that allows real-time display and comparison of horizontal sextant and DGPS determined positions. The integrated DGPS-AAPS tool was adopted with enthusiasm by the operating personnel for several reasons:

- The accuracy provided by DGPS-AAPS was conservatively estimated at 7.7 meters (2drms). Although this DGPS fix accuracy was not shown to be superior to that expected from horizontal sextant angles measured between landmarks ashore, it is certainly adequate to the task. Furthermore, DGPS removes the danger of error due to misidentification of landmarks, which can occur when using horizontal sextant angles. [Ref. 21:pp. 15-18]

- Productivity of aids to navigation crews is improved. The DGPS-AAPS combination provides a smooth, responsive display that allows dynamic repositioning of aids. For example, an off-station buoy that required "hours" to reposition using horizontal angles required only five minutes to drag to its desired position with the prototype system [Ref. 21:p. 17]. DGPS also provides the potential to continue work when landmarks are lost in low visibility.

- The system is easy to operate and reliable. Users required little training. DGPS is much easier to install, maintain, and operate than other microwave positioning systems used by the Research and Development Center. [Ref. 21:p. 6]

(2)   *Vessel Tactical Data Determination.* This involves precisely plotting the position of a vessel while it is underway to determine its turning,

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stopping, and accelerating characteristics. The R&D Center has developed software for this task which is now in the public domain.

(3) *Precise Track Following*. Coast Guard vessel effectiveness would be significantly enhanced in transiting preplanned tracks in support of Search and Rescue (SAR), mine-related operations, and ice operations.

d. *Vessel Traffic Control*

The recognized potential of DGPS for enhancing Vessel Traffic Service dependent surveillance has strengthened the political stimulus for a Coast Guard DGPS system. As was discussed in Chapter I, the *Exxon Valdez* grounding and massive oil spill in Prince William Sound, Alaska, brought the task of monitoring the precise position of tanker traffic to the forefront of national attention.

(1) *Vessel Traffic Service (VTS)*. A VTS system is intended to promote safety and efficiency by monitoring the area traffic, making information available about navigational hazards and vessel movements, and in certain cases, enforcing adherence to good navigational practice and communication procedures. To do this, the VTS must continually know the position of the participating vessels. While the master must remain in positive control of his or her own vessel, the VTS may govern the use of restricted space [Ref. 34:p. 16]. Typically, the VTS monitors the area by correlating vessel radio calls with their images detected by radar or video camera. However, DGPS could be used instead, in conjunction with dependent surveillance.

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(2)   Automated Dependent Surveillance (ADS). Dependent surveillance means that the target of interest is an active participant in the surveillance system, and actively transmits a message containing identification and position information. Voice reporting without supplementary monitoring is the simplest type of dependent surveillance; however, this method lacks any enforcement mechanism, and is often in error due to untimely or erroneous reporting. An Automated Dependent Surveillance (ADS) system uses a radio circuit to automatically transmit position information from a vessel of interest to a monitoring facility. A radionavigation system (such as GPS aided by DGPS) provides the position information directly to this circuit.

(3)   ADS/Radar Tradeoffs. The lack of enforceability is the major drawback to ADS, compared to radar:

> Vessels entering a VTS must be detected and identified in order for the
> VTS to be able to track vessel movement. The ability to detect an
> unwilling or unusual vessel is essential to the operation of the VTS....
> [Ref. 35:p. 40]

On the other hand, an ADS system has some definite advantages over a radar/voice radio arrangement. ADS eliminates possible confusion in correlating a radar return with a VTS participant, and eases language barrier difficulties. Also, in harbors with large areas to be monitored it may be far more efficient to use ADS (perhaps with supplementary radar or video at one or two key points) than to try to cover the entire area by radar. For this reason, the Coast Guard has chosen ADS over expansion of the existing radar system at VTS Prince William Sound. [Ref. 35:p. 34]

DGPS-based ADS would provide a desirable improvement in accuracy over radar. For some VTS applications accuracy is vital, as explained by a VTS officer:

> Consider two large ships in heavy fog approaching each other. The VTS watchstander's radar and computer tell him this could be dangerous,....Since he has been tracking the ships by name, he can make immediate radio contact to the bridge of each vessel. [Ref. 36]

However, unless the channel is very wide, or the radar is close to the subject vessels, radar accuracy may not be adequate to the task of detecting a vessel straying from its side of a channel.

> In normal practice radar range is set for a twelve nautical mile observation radius... this creates a maximum range error of 240 yards and a maximum azimuth error of 1250 yards... these error ranges decrease linearly as a function of the target range. [Ref. 35:p. 58]

DGPS *would* have sufficient accuracy to perform this function.

e. *Precise Air Navigation*

Coast Guard planning and budgeting documents do not prescribe DGPS for general aviation use. Planning documents do mention the utility of precise navigation for Coast Guard aircraft; however, it is not clear that ten meter (2drms) accuracy is now needed.

DGPS accuracy is not called for outside of the landing approach area: civil aviation policy states that basic GPS accuracy of 100 meters 2drms is suitable for all current requirements except precision approach and landing [Ref. 9:p. 4-4]. Airport precision approach and landing is an extremely demanding environment. For all weather operations, a vertical accuracy of 0.6 meters is called for [Ref. 9:p. 2-20]. The Instrument Landing System (ILS) was introduced in 1940

to serve this need, and is the standard civil landing system in the U.S and abroad through 1998 by international agreement. The Microwave Landing System (MLS) offers higher accuracy and greater flexibility, and has been selected to gradually replace ILS [Ref. 9:pp. 3-27, 3-28].

As was discussed in Chapter II, the current GPS satellite and control segment failure warning system does not warn of out-of-tolerance conditions soon enough [Ref. 9:pp. 3-40, 4-4]. DGPS could satisfy this integrity need. However, supplementary integrity monitoring techniques other than DGPS are being developed and may eventually correct this shortcoming, as previously discussed.

Thus, DGPS isn't *currently* intended for general navigational use by the aviation community. However, despite the strong official commitment to ILS and MLS, DOD, NASA, and the FAA are continuing to experiment with promising DGPS technology for aircraft approach and landing. In 1990, NASA completed 36 automated landings with simulated zero visibility using a DGPS navigation system integrated with an inertial navigation system. The same team is exploring DGPS utility in controlling taxiway traffic in low visibility [Ref. 37: p. 16]. DOD, in coordination with NASA and FAA, is investigating the feasibility of DGPS for landing at improvised sites using a light, person-transportable assembly. [Ref. 9:pp. 4-12, 4-13]

f. *Support of Other Agencies' DGPS Missions*

Planning documents state that any Coast Guard DGPS system should be compatible with other agencies' (e.g., NOAA, DMA, FAA and Army Corps

of Engineers) intended uses of reference station data and broadcasts [Ref. 31:p. 4].
For example, the experiments with DGPS aviation applications just discussed could
potentially fall in this category. The FAA's apparent intent to implement a GIC
network could also be a consideration. DGPS growth may come to resemble Loran,
which was initially intended for coastal maritime use but has recently been
expanded to provide mid-continent coverage for aviators.

   The U.S. Army Corps of Engineers is worthy of special note here
because of its research to apply DGPS in support of peacetime hydrographic
surveying and dredging in U.S. waters. The Corps of Engineers is investigating,
with the intention of developing, a real-time DGPS carrier phase tracking system
for very accurate positioning (a few centimeters) of moving platforms [Ref. 9:p.
4-13]. This technique appears to be limited to use within 20 kilometers of the
reference station now, but it is possible that interpolating/extrapolating from
multiple networked stations could extend this range. The design prototype using
one reference station is currently scheduled for delivery by September 1993 [Ref.
38:p. 43].

g. Support of Other Radionavigation Services

   Providing DGPS service would have an inherent synergy with the
Coast Guard's responsibilities as the lead agency for Civil GPS Service. DGPS
could help detect GPS problems and notify the user community, a service which
the existing GPS does not always provide in a timely fashion [Ref. 9:p. A-35]. The
system would also help the Coast Guard validate reports from the user community
on GPS performance problems. Interconnection between DGPS operations and the

Civil GPS service could be a future requirement. The recorded GPS information may become an element of an accident investigation, and should be safeguarded as a potential legal document. The GPSIC could serve as a depository for such historical DGPS information, which might also be useful for post-processing in non-navigational applications, such as hydrographic surveys. [Ref. 31:p. 4]

B. ASSUMPTIONS AND CONSIDERATIONS

This section documents several assumptions and issues surrounding DGPS service design. The assumptions bound the selection problem; there are far too many variables to consider all major permutations of DGPS implementations in the CEA process. For this study, we limit full analysis to two candidates that differ only in the manner in which the DGPS corrections are broadcast to the maritime users (by radiobeacon and by satellite). However, the considerations discussed here are reflected in the CEA structure developed in Chapter V, such that the model could be applied to evaluate alternatives to the assumptions in the following paragraphs.

1. Preplanned Product Improvement (P^3I)

The assumption is made that a P^3I approach will be used to develop a DGPS system which meets *existing* needs, and yet is designed to be expanded to incorporate new technology as it becomes available without developing a new system. This provides an early delivery of a simplified and affordable system (Coast Guard planning targets January 1, 1996) [Ref. 31: p. 2]. Probably the most critical aspect of the P^3I approach is the modularizing of the system to minimize future integration and retrofit problems. However, it also requires extra

capabilities which may not be utilized initially; such as power, cooling, memory, space, and communications ports. This entails increased initial cost, technical complexity, and vulnerability to "gold plating" criticism. [Ref. 39:p. 5-46 - 5-50]

P^{3}I goes beyond planned product improvement, which represents a change to the system that is generally anticipated but for which the basic system was not originally designed to accommodate. A classic example of P^{3}I is the Apple II microcomputer:

> The Apple II, introduced in 1976, had sales of approximately 500,000 in 1983, a remarkable achievement considering that the 1976-1983 period represents two or three generations in the rapidly evolving microcomputer world. Perhaps the most significant design feature of the Apple II that accounted for this performance is the inclusion of seven expansion "slots" in the initial design, allowing peripheral cards to be easily developed and easily inserted into the computer to enhance its capabilities.... Recent additions include cards to make the Apple a 16-bit computer; to introduce new operating systems; to triple speed... [Ref. 39:p. 5-50].

This P^{3}I approach affects most of the following assumptions in this section. Issues of standards, communications interfaces, system architecture, user fees, private sector radionavigation and military security requirements are all debatable. The CEA alternatives considered assume that the Coast Guard will not wait until technology is mature and needs are confirmed; instead, it will implement a simple, adequate system with planned improvement taken into account. Foresight in application of the P^{3}I approach will permit expansion to incorporate need and policy changes as well as technology; this facilitates incremental growth, as was discussed in paragraph A.2.d.

2. Standards

a. *International Standards*

In this study, it is assumed that compliance with established international standards is vital. In order to minimize the cost of user equipment, international consensus should be sought in selecting any radionavigation system configuration. Vessels should be able to use the same receiver equipment sets, and expect the same general standards of service in all DGPS equipped ports on their voyages.

There is intense foreign interest in building DGPS systems. Several European nations have pioneering programs underway, and cannot be expected to simply follow a U.S. lead. Unlike Loran, Omega, and GPS; DGPS has developed internationally, rather than as a primarily U.S. invention. There are many coordinating bodies that potentially could be, or already are, involved in the formation of DGPS international standards. The Radio Technical Commission for Maritime Services (RTCM) already has published *recommended standards* that are generalized for possible use with different data links, including radiobeacon or satellite DGPS transmitters [Ref. 7: p.1-1]. In addition, the International Association of Lighthouse Authorities (IALA) continues to foster technical discussions on DGPS as a part of its goal of developing international radionavigation guidelines. Traditionally, the International Maritime Organization (IMO) has provided less stringent radionavigation requirements for the maritime community than the International Civil Aeronautics Organization (ICAO) does for aviation [Ref. 9:p. 1-24]. The International Organization for Standards (ISO) and

International Telephone and Telegraph Consultative Committee (CCITT) could also play a role. [Ref. 40:pp. 1-11]

b. *Open Systems Interoperability Standards*

It is assumed that any desirable U.S. DGPS configuration will have the following "*open systems*" characteristics:

- System consists of multi-vendor interoperable modules (i.e., non-proprietary).

- Component module interface definitions are in terms of accepted standards (e.g., ISO, RTCM).

These guidelines apply to all components of a U.S. DGPS service. The open systems policy facilitates the writing of non-proprietary, unambiguous specifications, which encourage competition, in accordance with federal acquisition policy. It also encourages the re-use of previously developed hardware and software (either government produced or commercially available "off-the-shelf"), thus reducing costs. Another critical benefit of this open systems policy is that it allows individual subsystem modules to be replaced for system upgrades; growth can be accommodated without scrapping the entire old system.

In many areas, foresight will be needed to allow for adaptation to new standards as they mature. This includes the emerging Federal Information Processing Standards (FIPS), which specify GOSIP network communication protocols. GOSIP protocols are based upon the modular and hierarchical ISO Open Systems Interconnect reference model. Adherence to them allows the communications subsystem to reap P^3I benefits during expected future upgrades and interconnections. [Ref. 41:pp. 15-24]

The above concepts also should be applied to the fielded system's support structure. For example, repair tools would include Modular Automatic Test equipment, and documentation (configuration management) might use attractive portions of the DOD's Computer-aided Acquisition and Logistic Support (CALS) framework [Ref. 42:p. iv].

3. **Maritime Data Communications Interface**

The choosing of a DGPS broadcast channel to the maritime public carries implications beyond this one system to Coast Guard mobile communications systems in general. Looking towards the future: how does the Coast Guard intend to communicate data with its customers? There are many maritime data communications initiatives, including:

- The addition of digital selective calling to MF, HF, and VHF will allow the automatic establishment of communications. The technique may also be used to automatically make digital transmissions, such as identification, position, or distress information.

- Narrow Band Direct Printing is being implemented on MF and HF bands to broadcast teletype-format (digital) safety information to and receive various calls from the maritime public. These systems are called NAVTEX and SITOR, respectively.

- Inmarsat-C commercially provided service utilizes smaller, more versatile and less expensive shipboard antennas that will permit access by many more vessels to public satellite communications.

Clearly, these initiatives indicate a trend toward increased data communications between the maritime public and the Coast Guard. Traffic on these channels could include automated dependent surveillance or other position reports, *Notices to Mariners*, radionavigation information (including differential corrections), weather facsimile, time, and perhaps digital chart corrections

[Ref. 43:pp. 305, 316]. It will not be acceptable to require the mariner to buy another radio every time the Coast Guard discovers another data item to be communicated to or from the public. [Ref. 44:pp. 1-3]

Although a consolidated, standardized data communications interface to the maritime public is highly desirable, it is assumed that the Coast Guard DGPS service can not wait to see if or how this would be implemented. The modular P^{3}I approach previously discussed will be a vital part of both candidate solutions, such that either would be able to migrate to a different, standard Coast Guard digital broadcast channel if and when it matures.

4.   System Architecture

For this study, we assume the successful development of integrity monitoring and control methods that are generally the same for each configuration. Realistically, the system architecture could be allowed to vary to best suit the broadcast node, as described in Chapter II, C.2.d. However, this assumption permits consistent use of the available cost information.

5.   User fees

Planning documents require that DGPS "... be designed to protect the option of user fees for the future" [Ref. 31:p. 3]. Currently, all government provided radionavigation services are available to any suitably equipped user; there is no direct fee levied for the use of a specific system. Federal transportation policy is to institute user fees to recover costs from users of services that provide benefits to identifiable recipients, above and beyond those benefits accrued by the general public [Ref. 9:p. 1-23]. It is assumed that any user fee collection would not

be enforced through incorporating some technical mechanism in the broadcast signal. Rather, any such fee is assumed to be included in the vessel documentation or vessel user fee decal issuance process, or imposed upon each DGPS receiver before it is sold. Any fees do not affect the comparison of alternatives.

6.   Private Sector Radionavigation

It will be assumed that DGPS would continue to follow the historical precedent of U.S. radionavigation systems being operated by the government for reasons of safety, security and to enhance commerce. It should be recalled that radionavigation implies guiding the safe movement of a vehicle, as discussed in Chapter II. This assumption does *not* affect the continued or expanded use of existing private sector radio*location* service, which is appropriate for applications such as positioning and surveying over a limited area. [Ref. 9:p. 1-15, 1-24]

Current Coast Guard regulations (33 CFR 66.01-1(d)) prohibit operation of private electronic aids to navigation, with the exception of radar beacons (racons) and shore-based radar stations. In 1988, an "Advance Notice of Proposed Rulemaking" was published that invited public comment on the possibility of removing this restriction. Six responses were received: all endorsed allowing private radionavigation aids, with Coast Guard licensing and monitoring. Arguments *for* Coast Guard regulation and monitoring of private radionavigation aids include:

- **Timeliness.** Highly accurate radionavigation would be available for mariners that can afford such services much sooner than DGPS could be implemented by the Coast Guard. Innovation could also be superior in such a competitive market.

- Budget. Coast Guard budget requirements to provide radionavigation services would be reduced.

However, arguments *against* private radionavigation aids include:

- Liability. The Coast Guard would have to assume liability in the monitoring of a privately owned source system over which it would have limited control. Commercial ventures could remain vulnerable to lawsuits and bankruptcy in the face of maritime accidents, which could lead to the untimely discontinuation of service and loss of investment in user equipment.

- User Cost. The high cost of private systems puts them beyond the reach of most mariners. The overhead of administrative and technical measures needed to deny non-subscribers access to the commercial service would increase costs. In contrast, government-provided DGPS would encourage wide use of a beneficial safety-oriented service.

- Supervisory Complexity. The Coast Guard would incur sizeable administrative, equipment and field personnel costs in regulating many private radionavigation systems.

- Regulatory. It is anticipated that merchant vessel regulations will mandate the carrying of DGPS equipment. It would be undesirable to require the utilization of a particular commercial provider's service.

- Security. Should a national defense emergency arise in the coverage area, a government operated system would be more responsive to National Command Authority direction than numerous private sector systems could be.

For these reasons, the change proposed in 1988 appears unlikely to be implemented. [Ref. 45:pp. 1-2]

7. Military Security

It is assumed that the proposed DGPS system would not operate in a severely hostile environment, and so would not require immunity to jamming, imitative deception, or electromagnetic pulse effects. In fact, the FRP specifies that DGPS services could be suspended by the National Command Authority during dire emergency, presumably to deny accurate targeting to hostile forces [Ref. 9: pp.1-23, 2-33].

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It is also assumed that the Department of Defense (DOD) will not object to DGPS accuracy being made available to the general public on a routine basis. DOD has published its intent not to constrain the use of SPS-based DGPS service "... as long as applicable U.S. statutes and international agreements are adhered to." [Ref. 9:p. 4-2]

IV. REQUIREMENTS AND ALTERNATIVES

The mission objectives and assumptions from Chapter III provide the foundation for determining the requirements for a DGPS service. These requirements are discussed in Section A, below. In Section B, some alternative conceptual DGPS implementations are outlined, but not discussed in depth. Sections C and D give detailed discussions on the two selected alternatives: marine radiobeacons and dedicated AMSC satellite channels.

A. REQUIREMENTS

The assumptions stated in Chapter III are bounding criteria; while they are not repeated here, satisfaction of their conditions is necessary for any alternative to receive consideration. For example, pre-planned product improvement (P^3I) is assumed to be built-in, as is compliance with the RTCM SC-104 recommended standard. In effect, they are fixed requirements.

Other requirements for a Coast Guard DGPS come from taking the aggregate of the most demanding specifications of the mission objectives described in Chapter III. Of these, the Harbor and Harbor Approach (HHA) navigation mission requirements meet or exceed the requirements of the others. The FRP lists the requirements for safe navigation of large ships in the HHA phase as follows [Ref. 9:p. 2-23]:

- Predictable Accuracy: 8-20 meters (2drms)

- Coverage: U.S. harbors and harbor approaches

- Availability: 99.7%

- Fix Interval: six to ten seconds

- Fix Dimension: two

- Capacity: unlimited

- Ambiguity: resolvable with 99.9% confidence

GPS with any type of broadcast DGPS corrections inherently meets the last three requirements, so they are not discussed here. However, the first four items listed merit further discussion. There are also other requirements not specified by the FRP that are brought to light in the Coast Guard Tentative Operational Requirement (TOR). A total of eight criteria are given particular attention in the following paragraphs: accuracy, coverage, availability, fix interval, integrity, schedule, cost, and logistic support.

1. Accuracy

This requirement refers to the *predictable* accuracy (with respect to the geographic coordinates of the Earth). The predictable accuracy required at a given location within the coverage area depends upon the application, but the TOR has set a tentative requirement of 10 meters (2drms), referenced to WGS-84 [Ref. 31:p. 2]. While the FRP recognizes that better accuracy (one to five meter, 2drms) would be desirable for resource exploration, the TOR does not require it [Ref. 9:p. 2-23].

2. Coverage

Coverage of a DGPS system depends both on the range of the signal carrying the correction information, and on the validity of the information after some time delay, at a given distance from the reference station (see Figure 2-3:

"Coverage Cube"). The TOR has tentatively set coverage requirements for DGPS as the area 20 km seaward from each critical waterway of the United States [Ref. 31:p. 3]. This is taken as the required minimum; both of the alternatives extend well beyond this.

3. Availability

The availability of the host GPS system (i.e., GPS without differential corrections) approaches 100% for two dimensional surface marine applications. One less pseudorange is required to fix the position of the user at a known altitude (such as sea level) than for a situation where all three dimensions are unknown [Ref. 9:p. A-32]. Redundancy is inherent in the GPS satellite configuration.

The DGPS *system* 99.7% availability requirement will dictate the use of very reliable, mostly redundant DGPS system components. Redundancy may be designed into system components with different "depths". Consider the data integrity monitor function: if data from the differential reference receiver are checked at two independent locations, this is a "depth two" functional component. [Ref. 46:p. 288]

Let us consider the advantages of redundant components with a simplified example. Failure at any single point in a depth one DGPS network would cause system failure. We assume a four component system: differential reference station, broadcast integrity monitor, broadcast node, and network communications (including control station, if any). If each component has equal availability, then each must have an availability greater than 99.92% in order to achieve a system 99.7% availability.

$$p(Com_1 \; avail) * p(Com_2 \; avail) * p(Com_3 \; avail) * p(Com_4 \; avail)$$
$$= p(System \; avail)$$

However, if each functional component has an identical, redundant backup (depth two), each of these redundant subsystems needs only 97.3% availability; this is considerably less than the 99.9% figure for components in the configuration without redundancy.

$$\{1 - [p(Primary \; fail) * p(Backup \; fail)]\}^4 = p(System \; avail)$$

We are using availability to include both the technical capabilities of the radionavigation system and the physical characteristics of the environment [Ref. 9:p. A-2]. The availability values just computed assume there are no environmental events that prevent delivery of the transmitted signal to the user. Actually, the effects of any such occurrences must be included in availability forecasts. For example, the primary environmental threat to the host GPS system's availability is a severe ionospheric disturbance, which can cause loss of receiver lock. Such problems may arise in the near-equatorial regions, or in the aftermath of solar events; they are generally observed by all receivers in a locality [Ref. 47:p. 51].

4. Fix Interval

As defined by the FRP, the fix interval is the time between the determination of independent position fixes from the system. A fix interval of six seconds is specified by the FRP; however, this does not mean that a new

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pseudorange correction must be received by the user equipment every six seconds. In DGPS operation, "old" corrections may be repeatedly and beneficially applied to "new" GPS fixes at a rate determined by the user's navigation receiver. At the 50 bps data broadcast rate under the RTCM recommended standard, a DGPS message received 20 seconds previously should still give results within the 10 meter (2drms) accuracy requirement, even with selective availability errors in the GPS signals [Ref. 7:p. 4-34].

5. Integrity

Some degree of integrity certainly is required in any public DGPS radionavigation service, although it is not quantified in the FRP with the other HHA phase safe navigation requirements. The TOR specifies:

> An automatic, independent system should be employed to continuously monitor reference station operation to detect system abnormalities and failures. Automatic shutdown of the DGPS broadcast should occur in those instances. [Ref. 31:p. 2]

This does not give us a quantitative minimum time-to-alarm. Looking to existing radionavigation systems: Loran-C casualty procedures specify that when out-of-tolerance conditions occur, the control station watchstander should wait no longer than 60 seconds to "blink" the signal. This alerts users that system information may be erroneous [Ref. 48:p. 2-58]. We will assume this *60 second limit* to be the requirement for the DGPS system time-to-alarm.

In the restricted waters of the HHA environment a 60 second time-to-alarm might be dangerous. A highly desirable goal (but not a requirement) would be to meet the aviation non-precision approach standard: a warning of an unusable satellite pseudorange should arrive within 10 seconds [Ref. 16:p. 27].

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6. Schedule

DGPS should be operating in most U.S. coastal areas by 1 January 1996 [Ref. 31:p. 2].

7. Cost

System acquisition and implementation should not exceed $20 million; this value includes personnel, further development, and other implementation costs (listed in Chapter 5.A.6.b). [Ref. 31:p. 3]

8. Logistic Support

The following requirements are set by the TOR:

Mean time between failure (MTBF) must be at least 90 days, with a failure rate of less than 1% in 90 days. Mean down time should be no greater than two hours, and the system should be self-diagnostic with built-in test equipment. [Ref. 31:p. 4]

It is desirable to make use of existing Coast Guard resources, such as Loran-C stations. However, staffing levels at existing stations are inadequate to support additional workload, and more personnel may be required to perform new DGPS tasks. [Ref. 31:p. 4]

B. STATEMENT OF ALTERNATIVES

This thesis illustrates the proposed methodology by analyzing a radiobeacon broadcast and a dedicated satellite channel broadcast; these two were selected for different reasons. The Coast Guard Research and Development Center has focused its DGPS research on a radiobeacon-based system; thus, this alternative has been selected as the "baseline" against which any other alternative should be compared. Communications satellite transmission of DGPS signals was selected since it was

deemed to be an alternative in need of further research. It has generally been considered to be "too costly", and therefore unfeasible [Ref. 49]. However, the satellite communications industry and its related technology is changing rapidly; some forecasters anticipate a drastic decline in next-generation user equipment costs (these are discussed and used in Chapter V.C.1).

In making engineering decisions, it is desirable to list all possible candidates to guard against inadvertent omissions. Only after this listing should candidates be disqualified for being obviously unworthy of detailed analysis [Ref. 1:p. 40]. The following paragraphs list some of the known broadcast node candidates *besides marine radiobeacon and dedicated AMSC satellite channel*. This listing does not consider each in detail. Although most of these other alternatives clearly do not meet one or more of the previously discussed requirements or assumptions, some could be credible competitors. A more thorough exploration and documentation of all reasonably feasible alternatives should be performed as part of an operational selection of a DGPS implementation.

1. Alternatives in Lieu of DGPS

It is conceivable that DGPS might prove not to be the optimal means of satisfying the given requirements. For example:

- Generally available GPS accuracy and integrity could be improved by a change in defense policy and control technology, or hybrid GPS receiver integration with systems (see Chapter III.A.2.c and Chapter II.B.6.b).

- The Navy has been implementing Racal Decca HYPERFIX radionavigation chains to support mine-countermeasure tasks in some ports. However, the program has had calibration and availability difficulties, and has a dubious future [Ref. 50].

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- John E. Chance & Associates markets a satellite-based positioning service totally independent of GPS with three to five meter (2drms) accuracy. However, it has a limited coverage capability [Ref. 51, Ref. 3:p. 5].

There currently exist many other commercially available radiolocation services that could conceivably be adapted to provide the coverage, integrity and reliability required for general navigation. These solutions are likely to be costly, however [Ref. 7: p. 1-7].

2. Sercel's MF (Groundwave) Broadcast System

Sercel, Inc. is based in France. This system uses frequency diversity to broadcast DGPS information reliably despite atmospheric noise and fading. It broadcasts one carrier in the upper MF band and one carrier in the lower HF band. The transmission has an approximate range of 700 km over water and 100 km over land. Spectrum availability is an issue in considering this system. [Ref. 52:p. 600]

3. High Frequency Skywave System

This system would rely on the ionosphere to refract radio waves back to earth to transmit DGPS information to users up to 1000 km from the broadcast node. Coverage over land would be good, in the absence of man-made noise. Frequency diversity and overlapping coverage areas (to cover "skip zones") would probably be required. Ionospheric variability and spectrum availability are major concerns for this broadcast method. [Ref. 52:pp. 601-605, Ref. 53:Table 1]

4. VHF Line of Sight

The Coast Guard has a coastal VHF network in place, although it would need to be significantly upgraded to be capable of continuous DGPS transmissions. Digital communications to the marine public by VHF/FM for reasons other than

DGPS may be forthcoming in the future; see the discussion of a consolidated maritime data communications interface in Chapter III.B.3. DGPS service could be added to such a digital communications channel with off-the-shelf, competitively priced equipment. Limited range (10-60 nm) and spectrum availability are major concerns with this solution. [Ref. 52:pp. 601-602, Ref. 53:Table 1].

5. Cellular Radio

This commercially available mobile communications service is becoming increasingly available in U.S. coastal areas. However, such service is extremely expensive to the continuous user. It also has limited range. [Ref. 52:p. 602, Ref. 53:Table 1]

6. TV Vertical Blanking Interval (PBS Datacast)

This broadcast method is discussed briefly by Lanigan, et al.; it is currently used to provide color control to certain televisions, and closed captions for the hearing impaired. However, there are significant holes in the coverage areas, and broadcasts are not usually made 24 hours per day. [Ref. 52:p.602]

7. UHF Pseudolites

As discussed in Chapter II, a "Pseudolite" looks to the user like an extra satellite, and eliminates the need for a separate data link for the broadcast of corrections. The GPS receiver acquires the DGPS corrections directly. The RTCM has proposed a design which appears to solve the problem of pseudolite interference with nearby GPS users. The major problem with this solution appears to be its short range. [Ref. 7:p. 1-1, Ref. 53:Table 1]

8. **"Other" Satellite Channel DGPS Service**

It would be possible to communicate DGPS corrections by a satellite communication channel other than the American Mobile Satellite Corporation's (AMSC). Various companies currently are providing positioning (radiolocation) service using leased capacity on existing communications satellites. There are three communications satellite companies currently involved in the U.S. market: Comsat, Geostar, and Qualcom.

a. *Inmarsat and its U.S. Signatory, Comsat*

Inmarsat was formed under the auspices of the Inter-governmental Maritime Consultative Organization (IMCO), and is now based in London. It is a nonprofit (yet commercially operated), multinational organization originally chartered to provide the space segment necessary to facilitate communications in support of safety of life at sea, maritime efficiency, marine public correspondence, and radiodetermination [Ref. 54:pp. 593-595]. It has since expanded its functions to include aeronautical and land-mobile satellite service.

Comsat is the "for-profit" U.S. signatory of Inmarsat. It makes contributions to the capital requirements of Inmarsat in proportion to its 25% investment share, and also shares in its income. Comsat provides access to U.S. customers using the Inmarsat system. However, it is not permitted to compete with Geostar, AMSC and Qualcom in the U.S. land-mobile market. Comsat *is* permitted to provide aeronautical service to international flights arriving in the U.S. [Ref. 55:pp. 19-22].

Existing Inmarsat DGPS services require users to receive the continuous signals through large and expensive Inmarsat Standard-A antennas. The Inmarsat Standard-C channel suffers the disadvantage of an approximately 8-second delay caused by data interleaving. Plans are underway to evaluate provision of a higher power channel for DGPS, permitting use of smaller, omnidirectional user antennas (such as those used for Standard-C service) without such an interleaving delay. [Ref. 56:p. 4]

b. Geostar

This is a U.S. company formed to provide Radiodetermination Satellite Service (RDSS). Its positioning capability has been limited to communicating information derived by Loran, or another external system. However, Geostar was chartered to provide its own radiolocation services and a limited two-way data message capability. It used spread spectrum transmissions in the L-Band to communicate with mobile users. Geostar has recently gone bankrupt and ceased operations. [Ref. 57:pp. 23-33]

c. Qualcom

This company provides "OmniTRACS" positioning and two-way mobile data communications services using two leased Ku-Band (SHF) satellite transponders. Depending on the configuration, positioning is either accomplished by the mobile user's Loran-C receiver, or by satellite ranging. It does not currently use DGPS. [Ref. 57:p. 33]

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d. *Government Operated Space Segment*

It may eventually prove most cost-effective to put a communications transponder on a U.S. government operated satellite for the relay of DGPS signals. Again, the prospect of evolving to a consolidated maritime data communications interface is important to the future of DGPS, as discussed in Chapter III.B.3.

9. Pulse Position Modulation (PPM) of Loran-C Signals

This technique allows information transmission at a low data rate; DGPS data could conceivably be transmitted on this channel. Past successful communications trials have minimized impact on navigational performance of the Loran system by modulating only two of every eight pulses, and by maintaining an extremely low duty cycle [Ref. 58:p. 286]. It has not been shown that the system could tolerate the 50 bps minimum data rate of DGPS without degrading Loran-C performance.

C. MARINE RADIOBEACON MSK

The Coast Guard now operates marine radiobeacons that can be used for DGPS service. Minimum Shift Keying (MSK) can be used to transmit data without disturbing basic Radio Direction Finding (RDF) users. Since radiobeacon LF-MF signals propagate well as ground waves, they bend with the curvature of the earth and provide coverage well over the horizon without the need to rely on skywaves. In fact, the over-water coverage of longer-range radiobeacons seems to fairly well match the range over which a single DGPS reference station correction is valid [Ref. 52:p. 600].

Re-use of existing radiobeacon service spectrum is a major advantage of this alternative over most others. The regulation of radio frequency spectrum can be a tremendous barrier to a new system's implementation. Most new types of communications systems must obtain frequency allocations through a long and competitive review process before they can become operational.

1. Marine Radiobeacon Background

Radiobeacons are now used primarily for RDF, as discussed in Chapter II.A.4.c. Aeronautical radiobeacons and calibration radiobeacons are not addressed here. Federal policy on marine radiobeacons states:

> There are approximately 200 USCG-operated marine radiobeacons. Operation of this system will be continued indefinitely. The system is being modernized and expanded slightly with some reconfiguring to better serve the recreational boater who is the main user of the system.... Elimination of some long range bea⌐ ⟩ns and some changes in frequency assignments will result in more efficient ɹe of the allotted RF spectrum and allow for additional beacons in some areas if needed. [Ref. 9:p A-19]

Radiobeacons can be short, intermediate or long range, and can be sequenced or not. Sequenced beacons use time sequencing to operate in groups on the same frequency without mutual interference; they are being phased out in favor of continuous beacons.

- Short range radiobeacons are typically rated for a ten nautical mile (nm) range. They are usually located in harbors or waterways, and are equipped with 62.5 watt transmitters. Antenna height is typically 35 feet.

- Intermediate range radiobeacons are nominally rated for a 50 nm range. They make up the majority of the marine radiobeacon system. They provide for harbor approach, coastal, and Great Lakes navigation, and are equipped with 250 watt transmitters.

- Longer range radiobeacons provide coverage *over* 100 nm. They are located at widely separated sites of strategic importance to navigation, such as at

significant landfalls. They are equipped with 1000 watt transmitters. Antenna height is up to 125 feet.

Marine radiobeacons operate in the 285 to 325 kHz (LF-MF) band. The transmitted signal consists of two separate carrier frequencies: a continuous carrier at the assigned operating frequency and a keyed carrier 1.02 kHz higher which provides the Morse code identification characters for that beacon [Ref. 48:p. 1-1]. The continuous carrier tone is necessary for automatic RDF receivers to minimize jitter and hunting effects.

The following components are standard:

The equipment on a radiobeacon station consists of a coder, transmitter, an antenna coupler and an antenna. Other equipment used for monitoring station operation include an alarm-monitor unit, a reflected-power meter, and a receiver. In addition, sequenced stations have electronic timers... [Ref. 48:p. 1-2]

The alarm-monitor is actually a radiobeacon receiver which sets off an alarm if a discrepancy is detected. The reflected-power meter indicates the health of the transmission line, antenna coupler, and antenna.

The radiobeacon site is monitored remotely oy automatic or manual means. If a radiobeacon is not fitted for automatic monitoring, it is checked at least every eight hours by a Coast Guard radio communication receiver. Automated monitoring capabilities are not uniform, but should alert a watchstander if the following irregularities exist [Ref. 48:p. 1-3]:

- Incorrect timing of sequenced beacons

- Modulation that exceeds allowable range

- Low signal strength

- Improper code characteristic

The most recent Aid Control and Monitor System (ACMS) implementations may use phone and radio links to gather information from remote transmission sites for handling by a manned watchstation. These communication links permit the reporting of alarms from remote sites, or allow maintenance personnel to interrogate remote equipment operating parameters.

For its traditional RDF use, radiobeacon service range is the range at which it will provide a prescribed field intensity level to the user's antenna. These intensities have been established by international agreement to account for the variation of atmospheric noise with latitude, as follows [Ref. 48:p. 1-7]:

- 50 microvolts per meter for radiobeacons north of 40° N.
- 75 microvolts per meter for radiobeacons 40° N to 31° N.
- 100 microvolts per meter south of 31° N.

The system of radiobeacons is designed to avoid intrasystem interference. The difference between desired and undesired signal strengths, expressed as a ratio in decibels (dB) is known as the "protection ratio". It is set at 15 dB by Coast Guard policy. [Ref. 48:p. 1-7]

2. MSK Modulation

The present Coast Guard radiobeacon DGPS broadcast from Montauk Point, New York uses a type of phase modulation called Minimum Shift Keying (MSK). Existing hardware allows broadcast of RTCM SC-104 messages at a rate of 25, 50, 100, or 200 bps. The maximum data rate that could be modulated on one radiobeacon transmission without disrupting RDF users or adjacent beacons has not been determined. The phase modulation is performed on the 293 kHz center

frequency of the radiobeacon signal, not on an adjacent "sub-carrier". Each bit is represented by a 90° phase advance or delay of the carrier; advancing the phase indicates a binary "1". [Ref. 21:p. 10]

MSK was chosen for this application due to its excellent spectral efficiency. Other significant attributes of MSK, such as constant envelope, error rate performance, and self-synchronizing capability are well explained by Pasupathy in his 1977 IEEE paper [Ref. 59:p. 14]. Application of MSK to DGPS is discussed by Enge [Ref. 60:pp. 6-7].

3. Existing DGPS Broadcast

The generic broadcast node's function is discussed in Chapter II.C.2.c. The prototype DGPS broadcast facility at the Montauk Point high power radiobeacon fills this role.

A two-card radiobeacon MSK modulator circuit board set plugs into an ACMS-standard computer bus. This ACMS compatibility provides for remote control of the modulation of the radiobeacon broadcast from the differential reference station site [Ref. 21:p. 10].

The radiobeacon spectrum is heavily impacted by atmospheric noise, especially lightning. Multiple discharges tend to appear as a series of 20 or 30 "spikes" about 50 milliseconds apart. Therefore, the radiobeacon data channel may be characterized as a "burst" error channel, as opposed to a random error channel. Such conditions indicate that a convolutional code and interleaving scheme could be effective to combat atmospheric noise errors [Ref. 61:pp. 54-56]. Although such error detection and correction (beyond that defined in the RTCM recommended

standard) could be used to improve effective range, it would degrade timeliness, and has not been used in the Montauk Point tests [Ref. 21:p. 10]. The experimental broadcast monitor 20 nm away successfully received about 99.6% of radiobeacon messages broadcast during the normal working hours of the last six months of 1990 [Ref. 21:pp. 4-5].

The actual service range of the MSK radiobeacon broadcast remains to be determined, with and without additional error control schemes. Field trials have shown the system to provide good reception in excess of 300 nm; however, further research must be done to comprehensively address this question [Ref. 21:p. 11]. For the purposes of this study, we assume a 200 nm operational range can be achieved. This is well beyond the 20 km coverage set as the tentative requirement. Coverage is discussed further and illustrated in Chapter V.B.3.c.

The actual availability of basic radiobeacon service is not known precisely. The FRP now only requires 99% availability, and radiobeacons perform well in excess of this. Further investigation is needed to determine whether DGPS radiobeacons would require enhanced maintenance schedules or other changes to allow the entire DGPS system to meet the 99.7% availability required. Many sites are in remote locations; data link and power supply reliability may be problematic.

4. **User Segment**

Sercel, Inc. has announced DGPS user equipment that contains an internal radiobeacon MSK receiver. Magnavox has delivered a DGPS to Finland and Sweden, and supplies MSK user equipment; the design is based on radiobeacon MSK broadcasts fully compatible with the experimental USCG

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broadcasts from the Montauk Point radiobeacon. Other manufacturers are now working on prototype systems. This is discussed further in Chapter V. [Ref. 30]

D. Dedicated AMSC Satellite Channel

The Coast Guard could contract to have the American Mobile Satellite Corporation (AMSC) broadcast DGPS data on a dedicated channel. In Chapter V this alternative is compared with the radiobeacon-based alternative just discussed. The first AMSC satellite is scheduled for launch in 1994. Although not yet in service, this alternative appears to be a contender for effective DGPS service in the future. However, effectiveness and cost are both "risky", as discussed in Chapters V and VI. No AMSC communications satellites have been launched. User equipment prices and leased channel fees are forecast without the benefit of current market prices to extrapolate from. Thus, the satellite alternative has a *greater risk* than the radiobeacon alternative at this time. [Ref. 62]

1. AMSC Background

AMSC was formed as a consortium of several companies to provide Mobile Satellite Service (MSS) to air, land, and marine mobile users in the UHF L-Band in North America. In 1989 it was authorized to provide voice, data, and facsimile services up to 200 nm offshore. It is *required* to provide coverage of the continental U.S., Alaska, Hawaii, Puerto Rico, and the Virgin Islands. [Ref. 57:pp. 321, 439-461]

In order to encourage commercial applications of space technology, NASA has agreed to "barter" launch services valued at $56.5 million in exchange for experimental use of communications satellite capacity. Selected state and

federal agencies may be allocated use of about 15% of one satellite's capacity over two years. In the cost projections of Chapter V, satellite channel capacity for 1994 and 1995 is assumed to be free. [Ref. 62]

All AMSC services may be fully interconnected with the public telephone network. An important feature of satellite design is the incorporation of geographical "spot coverage". This allows frequencies to be reused, so long as adjacent spot beams avoid spectrum interference. This is especially appropriate for DGPS broadcasts that are generally not usable beyond a given distance from the differential reference station. Power expended to provide coverage over an area greater than a "spot" is wasted power. [Ref. 52:p. 604]

2.   Space Segment

AMSC was licensed in 1989 to launch and operate three spacecraft using 1.5-1.6 GHz (UHF: L-Band) for mobile communications, and 11-14 GHz (SHF: Ku-Band) for feeder-links. AMSC has agreed to cooperate with Canadian Telesat Mobile Inc. (TMI), so that each provides fully compatible redundant satellite capacity for the other in the event of space segment failure. [Ref. 62:p. 2]

3.   User Segment

AMSC is working on the development of three basic user antenna configurations, the smallest and least costly of which is omnidirectional (3" diameter, 1" high). Unfortunately, the lower gain available with this user antenna would require a more expensive, higher power satellite spot beam (EIRP = 25dB at 2400 bps) [Ref. 52:p. 604]. AMSC intends to promote standards-based,

non-proprietary user terminal designs [Ref. 62:p. 3]. This should encourage price competition and innovation among many terminal manufacturers.

4. Ground Segment

A conceptual DGPS/AMSC data communication architecture is shown in Figure 4-1. This segment is composed of one operational Network Control System (satellite control and network management) and many fixed "feederlink" stations. These feederlink stations are fixed gateway or base stations that connect to public networks or private facilities, respectively [Ref. 57: p.448-451]. For a DGPS service, these would be the interfaces to Coast Guard DGPS facilities; the Coast Guard would provide a multiplexed data stream carrying information from many differential reference stations to each. Gateways and base stations are distributed throughout AMSC's coverage area to reduce long-distance landline costs.

This architecture implies the multiplexing of information from many reference stations and integrity monitors at a few centralized Coast Guard DGPS control facilities. Such a system may be particularly suited to growth towards a "wide area" or "extended" DGPS service, using a few networked differential reference stations to broadcast a multi-station solution to users [Ref. 63].

It is equally important that redundancy be designed into the terrestrial components as in the space segment. As with the space segment, the TMI Network Control System will provide this redundancy for satellite telemetry and network management functions; the implementation must provide for rapid changeover in the case of failure. Ground segment design and control mechanisms also should provide for DGPS connectivity to alternate feederlink stations. These

Figure 4-1. Conceptual DGPS/Satellite Communications Architecture

backup stations should be located in different locales, so that a natural disaster or blackout would be very unlikely to occur simultaneously at a feederlink and its alternate.

5. Services and Marketing

AMSC intends to rely heavily on "authorized service providers" to interface with customers on its behalf, as well as to provide value-added services. [Ref. 62]

V. COST-EFFECTIVENESS METHODOLOGY

A. METHODOLOGY

The primary emphasis of this thesis is to show how the DGPS project's decision making and planning may be aided by comparing technological alternatives using Cost-Effectiveness Analysis (CEA). This method is essentially a means of quantifying "effectiveness per dollar of cost" for various alternatives; the value of this ratio will be highest for the superior alternative. This section describes the *general* theory behind application of the CEA problem-solving approach to DGPS service design. Most details specific to DGPS follow in subsequent sections, including technical criteria and estimated system costs.

1.   Motivation for Performing CEA

The project's non-major system categorization (less than $20 million investment cost) allows choosing of the best tools to implement a project of this size. Although a CEA is not required, it is a tool that can give a return well worth its moderate difficulty in this case. Applying CEA techniques to the proposed USCG DGPS navigation system would help decision makers quantify the trade-offs and would permit:

- The various parties to a decision to observe the basis for each other's conclusion.

- The decision maker to draw on the intuitions and judgements of his/her staff without abdicating decision making prerogative.

- Sensitivity analyses to be made of variations in the estimates. [Ref. 64]

The CEA procedure to be described incorporates consideration of risk and life cycle cost. This structure is especially suited to refinement and adaptation in support of decision making in an environment of technological and policy change.

2. Overview of CEA Steps

The essential steps of cost-effectiveness analysis adapted for DGPS implementation planning are:

- define system objectives (Chapter III)

- state evaluation assumptions (Chapter III)

- identify essential mission requirements (Chapter IV)

- list alternatives (Chapter IV)

- establish effectiveness measures (Chapter V)

- evaluate alternatives' overall effectiveness (Chapter V)

- develop cost data (Chapter V)

- assess effectiveness and cost risks (Chapter VI)

- perform cost-effectiveness computations (Chapter VI)

- perform sensitivity analysis (Chapter VI) [Refs. 65, 66, 67]

3. Objectives, Assumptions and Requirements for DGPS

These first three steps are arguably the most important steps. They have been performed in the previous two chapters, drawing primarily upon results published in the Coast Guard's DGPS Tentative Operational Requirement (TOR) [Ref. 31] and Federal Radionavigation Plan (FRP) [Ref. 9].

4. Statement of Alternatives and Refinement

Alternatives were identified in Chapter IV, but not comprehensively. In this study, the alternatives to be compared have been configured so as to allow the use of available Coast Guard DGPS planning costs. Therefore, we have generally adhered to the structure of the DGPS visualized in tentative plans. The following description of the alternative refinement process is given to illustrate how a comprehensive DGPS analysis should be performed.

The first step of this stage should be to note all reasonably feasible alternatives. Before carrying out further analysis, a cursory review should be performed to eliminate those that are:

- technically infeasible

- operationally infeasible due to overriding considerations delineated in the assumptions/requirements statement

- economically unacceptable (over budget) [Ref. 65:p. 5]

At this point, variations of individual alternatives may be narrowed down. The optimal variant of a general type of alternative may be identified, so a full CEA of each variation is unnecessary. For example, for each alternative, the DGPS analyst should determine:

- the best network configuration in terms of control:reference station:broadcast node ratios.

- the optimal differential reference station spacing and system coverage.

- the optimal transmission rate.

The data rate of the channel may limit the effective differential reference station:broadcast node ratio. Manpower analysis and the availability of existing robust communications links will be important to control station assignment.

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The data update rate should not be firmly fixed in the earlier requirements section unless mandated by international standards. Update rate is a key parameter in determining accuracy, and can be an important tradeoff in this optimization [Ref. 68:p. 211].

The optimal coverage for *each* general DGPS scheme could be estimated by a very "rough-cut" and judgmental marginal-cost equated to marginal-utility approximation. To support such evaluations, the FRP provides maritime requirements/benefits guidelines [Ref. 9:pp. 2-1 - 2-36]. In accordance with economic theory, curves of dollars/unit-coverage vs. coverage-area could be plotted to find the optimal design. The FRP states:

> The process to determine requirements involves: ... Evaluation of the economic needs in terms of service needed to provide cost-effective benefits to commerce and the public at large. This involves a detailed study of the desired service by user group measured against the benefits obtained. [Ref.9:p. 2-2]

It is impossible, however, to execute this process rigorously; the marginal-utility is too hard to fix in terms of dollars. Commercial efficiency produces obvious utility, but it is not easy to quantify; measuring improvement of safety to human life and the environment is harder yet [Ref. 9:p. 1-22]. Marginal-utility is also exceptionally difficult to forecast due to the unprecedented accuracy of DGPS. As discussed in previous chapters, even system-educated potential users cannot estimate their own demand until they've had an opportunity to make use of dramatically new capabilities. Another complication is that user demand will increase dramatically as complementary technologies such as ECDIS (Electronic Chart Display Systems) are developed. Blanchard sums up these problems in his discussion of the use of CEA as a tool for engineering design:

Cost-effectiveness relates to the measure of a system in terms of mission fulfillment (system effectiveness)... *True* cost-effectiveness is impossible to measure since there are many factors that influence the operation and support of a system that cannot realistically be quantified....thus, it is common to employ specific cost-effectiveness *figures of merit* (FOM)... to allow comparison of alternatives on the basis of the relative merits of each. [Ref. 1:pp. 136-137]

5.   Effectiveness Measures

In the CEA process, a model of the total system effectiveness of an alternative is necessary to consider all system design trade-offs. This is done using a hierarchical weighting scheme: several "elemental" Measures Of Performance (MOP's) are weighted and summed to produce one Figure Of Merit (FOM). All of the system FOM's are weighted and summed to produce the overall system effectiveness.

$$FOM_j = \frac{\sum_{1}^{i}(MOP_iUtility * MOP_iWeight)}{\sum_{1}^{i}(MOP_iWeight)}$$

$$EFFECTIVENESS = \frac{\sum_{1}^{j}(FOM_j * FOM_jWeight)}{\sum_{1}^{j}(FOM_jWeight)}$$

a.   *Identification of MOP's*

Radionavigation-oriented measures are best suited to quantifying the desirable traits of a DGPS service. Even though the transmission of DGPS signals is technically more a communication system than it is a traditional

radionavigation system, signal-oriented communications parameters [Ref. 66] do not quantify the essential effectiveness traits as well as radionavigation-oriented measures do.

System costs are not generally considered in MOP's; they are included in the life-cycle cost calculations. There are rare exceptions, however. For example, we use the "Technical Flexibility" MOP to consider the possibility that user equipment might have to be replaced (at a large dollar cost) in the event of a future change of broadcast mediums. In this case, the expected value of the cost is more readily accounted for in the "effectiveness dimension" than as a cost.

b. Identification of FOM's

As used here, a Figure of Merit (FOM) is a summation of various weighted MOP's. A single MOP could contribute to more than one FOM. The MOP's and FOM's for the DGPS analysis are proposed in Section B of this chapter. The relative weights (contributions) of MOP's to each FOM, and FOM's to overall effectiveness should be assigned before any rating is done. This helps to avoid the inadvertent inclusion of personal bias in the model.

c. Calculation of Overall Effectiveness

The effectiveness modeling procedure now calls for assigning utilities, and calculating the FOM expected values. The calculation of expanded overall effectiveness for each alternative will involve differently weighting each FOM before taking the sum of them.

If "risk" (i.e., the size of the probability distribution about the expected value, or the degree of uncertainty) is estimated for each FOM rating,

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statistical techniques for combining these factors must be applied in order to produce the proper aggregate risk. However, it also would be reasonable (and much simpler) to estimate the effectiveness risk for each alternative directly, without going through the procedure of estimating risks at the FOM level and combining them later. This is the approach used in this thesis; effectiveness risk is estimated as part of analysis.

6. Develop Cost Data

a. Cost Analysis Methods

There are three types of cost analysis techniques prescribed for Coast Guard systems acquisition use: Analogy, Parametric Model, and Engineering (Work Breakdown Structure). For major systems, the first two methods are typically used in the early developmental stages. By the production phase, detailed engineering estimates should be made by extrapolating from known values [Ref. 69:p. 5-16].

The Coast Guard operated (service provider) portion of the system would apply existing technology and commercially available equipment with forecastable costs. Therefore, the engineering WBS technique has been used by Coast Guard planners for the DGPS project, even though it is in its conceptual stage. This breakdown is not presented here, but its resultant totals have been incorporated in the cost spreadsheets for both alternatives. [Ref. 70]

On the other hand, future costs and quantities of user equipment require application of the analogy technique, as will be seen in the following section. Since the government would provide the DGPS system in the interest of

the public good, Federal policy mandates that analysis consider user equipment as part of system cost [Ref. 9:p. 1-26]. We may determine the current price of off-the-shelf equipment, component parts or services whenever possible, and extrapolate for future costs. The price of DGPS user equipment is falling rapidly, and can be expected to continue to follow a "progress" curve decline. Analogy with mature navigation systems is useful in determining the type and rate of decline (see Section C.1.).

b. Life-Cycle Costs

Investment costs are relatively small compared to the aggregate of life-cycle research and development, production and investment, operation and support, and salvage and disposal costs. It is reasonable to assume that salvage value will approximately offset disposal costs, and this last phase of the life-cycle may be ignored. The following is a detailed listing of cost elements by phase; the R&D, investment, and operations elements are generally incorporated in the Coast Guard planning costs used in the Appendix A DGPS estimates. [Ref. 71:p. 267]

R&D	INVESTMENT	OPERATIONS	SALVAGE/DISP
Planning	Production	Personnel	Inventory
Management	Planning/Mgt	Consumables	Closeout
Engineering	Init Spares	Support	Shipping
Test	Training	Facilities	Data Mgt
Evaluation	Suprt Equip	Maintenance	Refurbishing
Equipment	Tech Manuals	Shipping	Waste Mgt
Facilities	Test & Engin	Tech Data	
	Facilities	Supply Mgt	
	Suprt Fac	Modification	
	Init Transpo	Training	

c. Cost Summary

Discounting techniques should be incorporated to account for the future value of money at some point in the cost computations. OMB circular A-94

prescribes a rate of 10%, applied using a discount factor equal to $1/(1+r)^t$ [Ref. 72].
For this CEA, discounting is performed as the last calculation on each page of the
cost spreadsheets (see Appendix A).

7.   Risk Assessment

The cost analysis procedure should make cost risk estimates. It is
preferable in this case to make a direct estimate of risk, as previously discussed for
the effectiveness dimension. In this study, this estimate is made in the analysis of
Chapter VI for each alternative.

8.   Cost-Effectiveness Computations

A single table is created to summarize the results of previous
effectiveness and cost determinations. Since the comparison of alternative DGPS
systems considers alternatives with unequal cost and unequal effectiveness, the
table will provide a basis for the graphical analysis of the next step.

A planar cost-effectiveness graph may be used to compare alternatives,
as illustrated in Figure 5-1. The expected values of life-cycle costs, including public
user set expenses, are plotted on the X-axis. The expected values of effectiveness
are plotted on the Y-axis. Effectiveness and cost risks will eventually be drawn as
circles or ellipses around the plotted alternatives. The analyst may plot the
domain of feasibility defined by the cost ceiling and minimum effectiveness, if
desired (not shown here). Points outside the domain of feasibility are not viable
candidates. The slopes of the lines drawn from the origin to the alternatives show
us C-E ratios. Slope represents effectiveness per dollar of cost, and is shown in
Figure 5-1 by the angle in the lower left corner. This may also be done

numerically. Large slopes and large numerical C-E ratios are generally preferable when budget constraints are pressing.
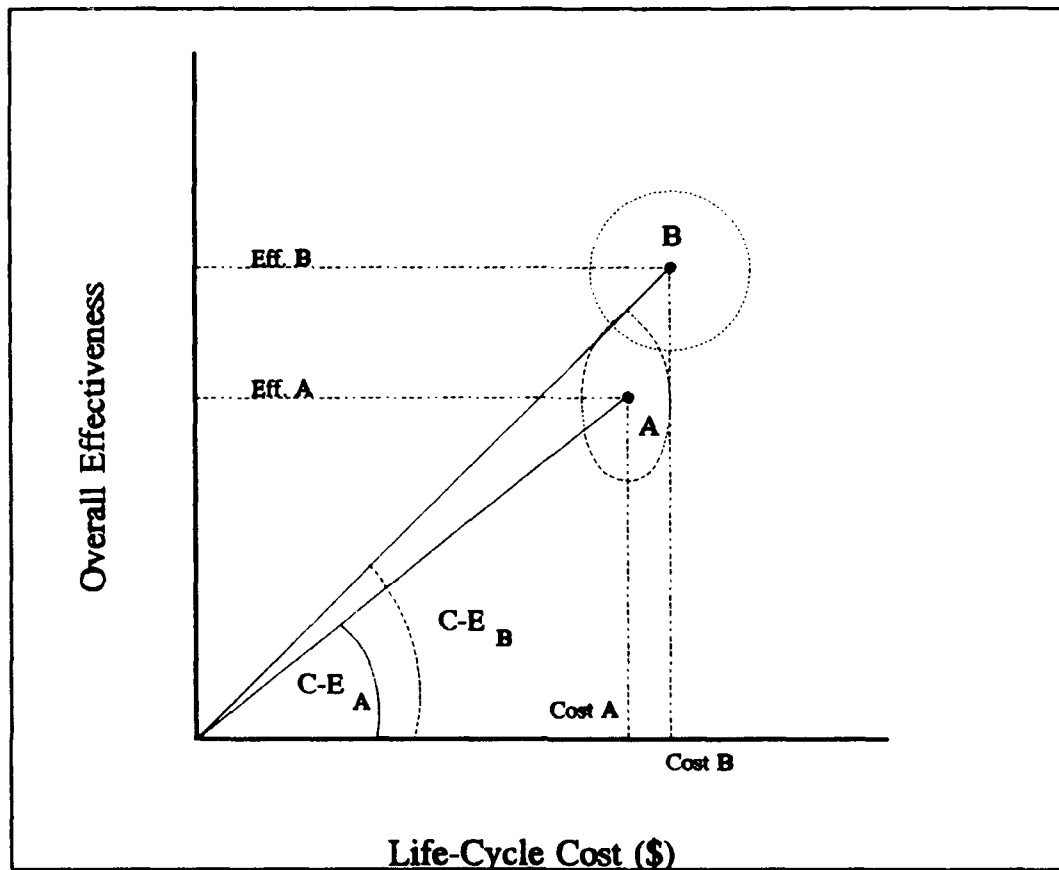
Figure 5-1. Comparison of Hypothetical Alternatives: Planar Cost-Effectiveness Graph [after Ref. 67]

9. Sensitivity Analysis

Sensitivity analysis is performed in Chapter VI. The goal of this step is to identify those areas in which relatively minor changes in parameters could change the choice of an "optimal" alternative.

This includes estimating "risk": the size of the probability distribution about the expected values of overall effectiveness and life-cycle cost for each alternative. The statistical confidence interval (usually "2 sigma", or 95%) is

plotted about the expected value on each axis of the Cost-Effectiveness (C-E) graph. The realm of possibility defined by the ellipse around any alternative is a good representation of its risk in each dimension. In this case, large risks will weigh heavily against an alternative due to the need to field a DGPS system quickly.

There are other uncertain values to be considered in addition to cost and effectiveness estimates. The following quantities also should be adjusted, and the evaluation recomputed to investigate their significance: market price trend (slope factor), number of user DGPS sets, MOP and FOM weights. [Ref. 65:p. 19]

10. Conclusions on the CEA Process

The result of the analysis process should not be considered a definitive "answer" as to which implementation alternative to adopt. Subjective evaluations are implicit in the methodology, and the result can only be as objective and accurate as the analyst. Rather, the CEA process should be considered a tool to aid the decision maker in grasping the appropriate information.

B. EFFECTIVENESS MEASURES

This section develops measures and compares the strengths and weaknesses of the two DGPS alternatives selected in Chapter IV. It is beyond the scope of this study to comprehensively address the many other technically feasible alternatives in this study. However, by selecting and developing the following effectiveness measures it is possible to create a structure that can be useful for evaluating various configurations of a nationwide marine DGPS system with minimal modification.

There are ten standard radionavigation system parameters prescribed in the FRP. Some of these are well suited to this CEA; for example, accuracy, availability, and integrity (defined in Chapter II), come from that list. Others have been modified, such as signal characteristics. Some have not been included because they are essential requirements, and would be automatic disqualifiers if not met (such as "ambiguity"). Addressing important criteria has dictated the use of five primary Figures of Merit (FOM's), as defined by the following five subparagraphs. Each is made up of several Measures of Performance (MOP's).

In practice, definition of MOP's and FOM's precedes the assignment of weights, which precedes the assignment of utilities for each alternative. This sequence discourages the inclusion of preconceived bias in the model. However, in the interests of clarity, we will define each MOP and immediately illustrate it in terms of the DGPS alternatives being evaluated; see Tables 5-1 and 5-2 for the numerical values assigned.

1. Accuracy

As was noted in Chapter II.C.1, the important design considerations for accuracy of a DGPS system are the baseline distance between the reference station and the user, and the age of a correction when it is applied to the measured pseudorange by the user. The age of the oldest corrections will be the sum of the update interval and the transmission latency.

a. *Update Rate*

The DGPS Type 1 Message correction for each satellite pseudorange will be broadcast at intervals that depend on several factors. The estimations

Tables 5-1 and 5-2. MOP Ratings and FOM Expected Values

Table 5-1: Measure of Performance Ratings

ACCURACY	Weight MOP	Utility RBn	Utility Sat
Update Rate	4	5	6
Latency	4	5	4
RefSta Spacing	2	5	5
ACCURACY WTed TOTAL		5	5

AVAILABILITY	Weight MOP	Utility RBn	Utility Sat
Dependability	10	5	5
Resist. EMI	3	5	5
Resist Iono Var	2	5	3
Resist MP & Obs	5	5	4
Graceful Degr.	5	5	3
AVAILABILITY WT TOTAL		5	4.24

COVERAGE	Weight MOP	Utility RBn	Utility Sat
HHA/Coastal	10	5	5
Ocean Phase	5	5	5
Inland Waterway	5	5	9
COVERAGE WTed TOTAL		5	6

INTEGRITY	Weight MOP	Utility RBn	Utility Sat
Timeliness	4	5	4
Index of Safety	6	5	5
INTEGRITY WTed TOTAL		5	4.6

ADAPTABILITY	Weight MOP	Utility RBn	Utility Sat
International	3	5	3
Interagency	3	5	7
Technical Flex.	6	5	7
Open Sys Int	3	5	5
Spectral Eff.	6	5	5
Institutional	6	5	3
ADAPTABILITY WT TOTAL		5	5

Table 5-2: Figure of Merit Expected Val

FOM	WT FO	RBn FOM ExpVal	Sat FOM ExpVal
ACCURACY WTed	5	5	5
AVAILABILITY WTe	10	5	4.24
COVERAGE WTed	5	5	6
INTEGRITY WTed	10	5	4.6
ADAPTABILITY WTd	10	5	5
Overall Wt Eff		5	4.835

made in Chapter II.C.3. assumed the minimum data rate of the broadcast medium allowed by the RTCM recommended standard. However, a higher data rate is permissible and would avoid the need to use the oldest corrections.

b. Latency

How old will a "new" correction be when it can be applied to the user's navigation solution? We will use this measure of effectiveness to refer to the time lag between the moment the GPS signal arrives at the reference station until the moment the broadcast correction is available to be applied to the user's measured GPS pseudorange. A representative estimate of these delays for a *satellite-based* integrity monitoring system is [Ref. 16:p. 43]:

- Processing of GPS signal: 0.2 - 1.2 sec

- Processing of data and formatting: 0.3 sec

- Reference to broadcast station propagation: 0.1 - 0.3 sec

- Broadcast station processing time: 0.2 sec

- Broadcast station data processing and formatting: 1.2 -4.4 sec

- Broadcast station to user propagation time: 0.3 sec

- Receiver demodulation and data processing: 0.4 sec

Differences in the latency seen using each alternative arise in the transmission from reference station to broadcast station to the user; processing time within the reference station and at the user site is assumed the same. The radiobeacon alternative would experience a negligible broadcast propagation time, and perhaps a slightly shorter reference to broadcast station propagation time; let

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us say a total 0.4 second advantage. Otherwise the two alternatives would be equal.

We will assume uncoded broadcasts for both alternatives; that is, there are no additional interleaving or parity algorithms incorporated on top of the RTCM recommended parity algorithm. This assumption would not hold if forward error correction were to be used to correct detection errors of radiobeacon transmissions at long distances, at the cost of increased transmission time.

c. *Reference Station Spacing*

How far is the user from the reference station? Reference station spacing is the only design criterion that affects spatial decorrelation. Also, this distance may degrade the DOP if a satellite visible to the user is not visible to the reference station, and can not be used in the DGPS solution. In the cases we are considering, the number and spacing of the reference stations are the same.

2. Availability

a. *Component Dependability*

This MOP measures a system's resistance to component failure causing interruption of service. Although reliable individual components are important, redundancy is critical to achieving high availability. Ideally, there should be no "single point of failure"; each part should have a backup.

The two alternatives under consideration will be identical except for the data link from the reference station to the broadcast station, and the broadcast station itself. Unfortunately, the designs of both systems are currently in such a formative stage that any advantage between the two cannot be determined. For a

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radiobeacon DGPS system with 44 broadcast nodes there should be enough overlapping coverage to permit users with mature MSK receivers to quickly switch from a catastrophically failing beacon to an adjacent healthy one. Similarly, AMSC intends to have redundant satellite capacity through a cooperative agreement with Canadian Telesat Mobile Inc.

b. Resistance to EMI

How much will the presence of nearby power lines or lightning storms degrade signal reception? Manmade and natural interference will cause noise that will restrict the coverage and/or availability of both systems. The precise degree to which each will be affected is unknown at this time.

c. Resistance to Ionospheric Variations

This general phenomenon was discussed in Chapter IV.A.3. Satellite transmissions will be affected by severe ionospheric events. It is expected that radiobeacon communications will be much less degraded, if at all. Although the propagation time of the radiobeacon LF-MF signal may be changed, such events should not block reception by users in the coverage area. Therefore, it is anticipated that the radiobeacon alternative will have an advantage over satellites in this MOP.

d. Resistance to Multipath and Signal Obstruction

How well will signals be received in the vicinity of bridges and other obstructing or reflecting metal structures? Radiobeacon transmissions are in the LF and MF bands, and so bend around obstructions better than do line-of-sight satellite UHF transmissions. However, the satellite is overhead, and so is likely to

encounter fewer obstacles (e.g., mountains) in proceeding to a user than would the ground wave of the radiobeacon. In the maritime HHA environment envisioned, it is anticipated that the radiobeacon alternative will have an advantage over satellites in this MOP.

e. *Graceful Degradation*

As was discussed under component dependability above, redundant systems must provide for service reacquisition in event of momentary loss. For DGPS, non-adjacent momentary losses aren't too bad, so long as the resultant increase in the age of the correction being applied doesn't become excessive. The time required to switch to any alternate broadcast source is important to this MOP. Also, the spatial decorrelation associated with the user acquiring its corrections from this new source should be considered.

In the case of radiobeacons, the switch to the alternate source should be rapid, requiring only a decision and reacquisition by the user receiver. For the satellite alternative, a complex transfer of data link paths must take place that surely would require much more time. However, switching to an alternate radiobeacon would imply the loss of the corrections from the closest reference station, even if it were working perfectly. The redundant satellite transmission would be capable of broadcasting all the reference stations, as before. Overall, the radiobeacon is deemed to have an advantage in this MOP, since time delay is generally more damaging than spatial decorrelation.

3. Coverage

See Figures 5-2 and 5-3 for the projected coverage areas for the two alternatives. Coverage of a DGPS system depends both on the range of the signal carrying the correction information, and upon the validity of the information at a given distance from the reference station. Coverage is limited by the ability to receive the broadcast signal over long distances in the presence of noise. Accuracy and coverage are related in that coverage ceases to be assumed when distance from the reference station causes accuracy to exceed the required limits (spatial decorrelation). It is also limited by the probability of poor geometry arising when satellites available to the user are not visible at the reference station.

It would appear that significant portions of both Mexican and Canadian coastal and inland territory would be coincidentally covered by the lease of AMSC spot beams for DGPS transmissions. The potential for cost-sharing exists, but is not considered here.

a. HHA and Coastal Phases

The actual coverage and number of spot beams to be implemented by AMSC is subject to final system definition and regulatory approval. However, satellite spot beam coverage of all required areas is assumed feasible by using six spot beams as specified in 1990. In addition, we will assume that Hawaii will be served by a side lobe of the Alaskan beam. Given these assumptions, both alternatives provide roughly equivalent coverage in these phases.
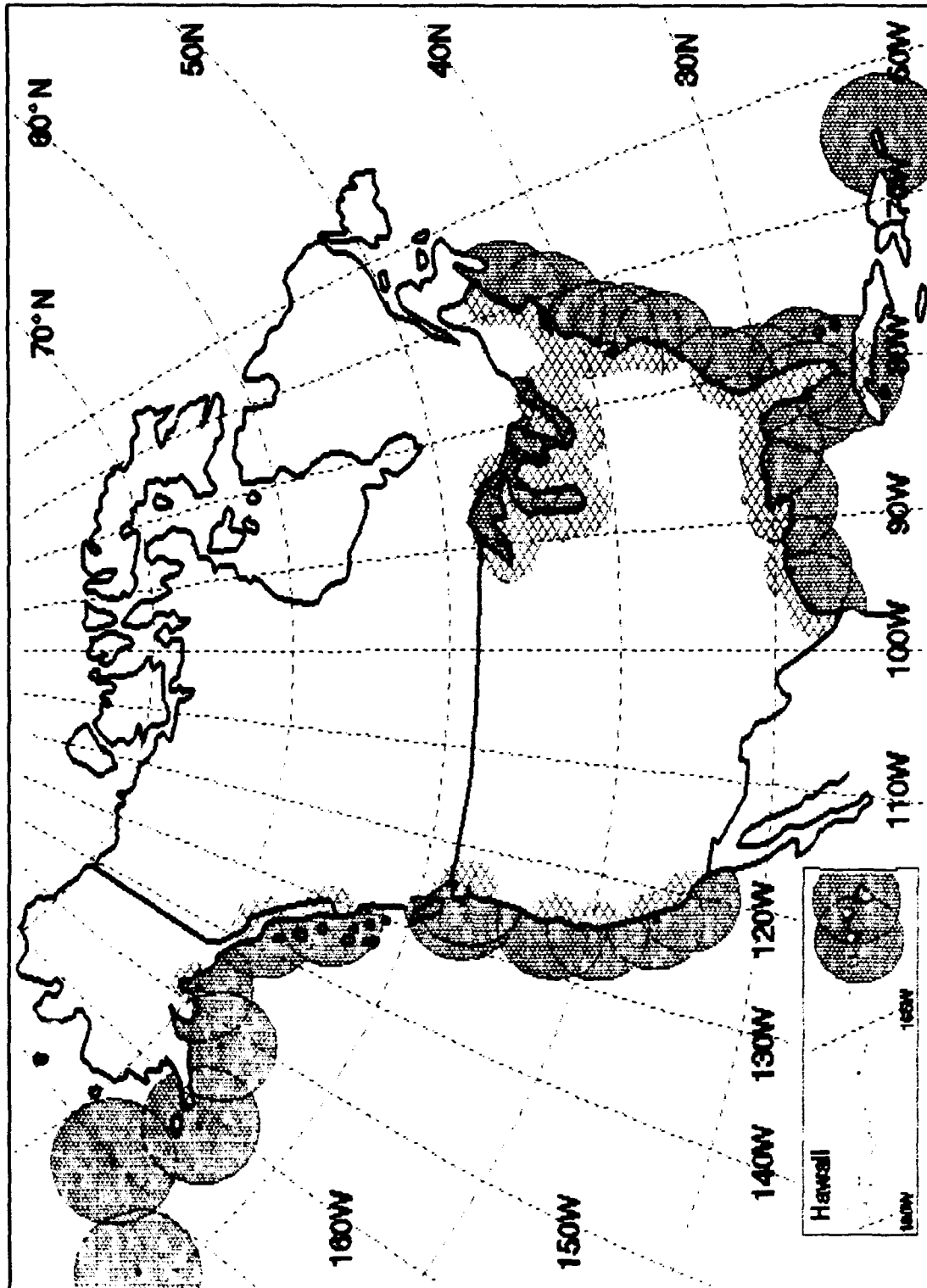
Figure 5-2. Projected Coverage Area: Radiobeacon Alternative
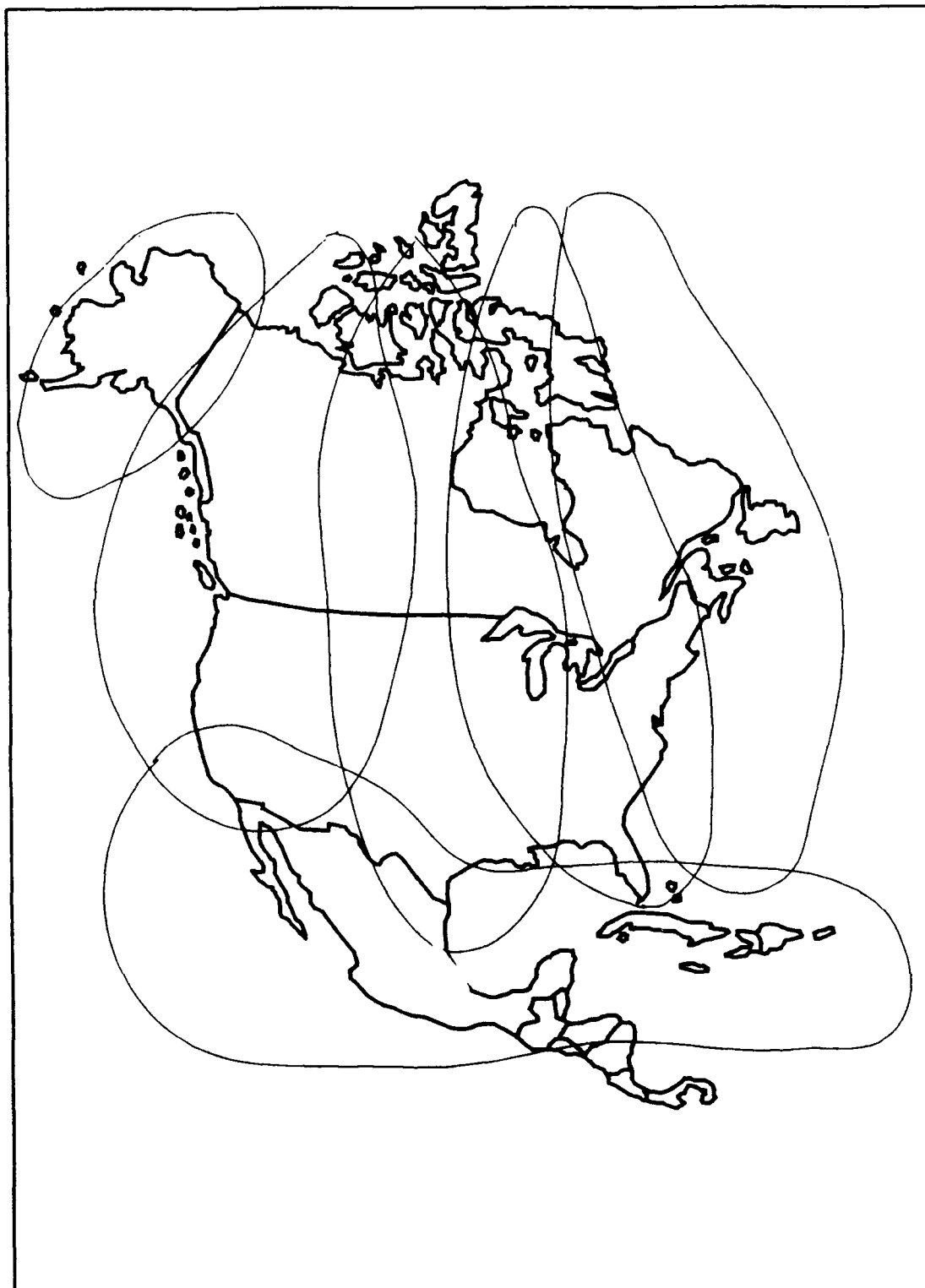
Figure 5-3. Projected Coverage Area: Satellite
Alternative [Ref. 62, taken from promotional literature]

b. Ocean Phase

In general, the coverage of the satellite spot beams is dependent on regulatory considerations: they are limited to within 200 nm of the coast. The coverage of the radiobeacon DGPS broadcast is heavily dependent upon the data rate and coding used by the specific system used. We will assume 200 nm offshore coverage for this option as well, in the absence of forward error correction [Ref. 21:p. 6].

c. Inland Phase

The alignment of AMSC spot beams shown in Figure 5-3 may not be final. However, it appears likely that most inland areas will be covered by the satellite spot beams required for HHA phase coverage. This inland coverage area would be much larger than that resulting from implementation of DGPS using maritime radiobeacons, whose signal propagates less efficiently over land than over sea. The radiobeacon coverage illustrated in Figure 5-2 assumes 200 nm coverage over seawater, and 55% of this (110nm) over land [Ref. 61:p. 56]. This favors the satellite alternative.

4. Integrity

Integrity mechanisms must be provided to verify that the GPS pseudoranges are within usable tolerances and that the DGPS broadcast itself is transmitting correct information.

a. Timeliness

This MOP quantifies the negative impact of requiring additional time before warning a user of an unusable pseudorange. For example, if a

particular broadcast medium were particularly subject to error, the integrity monitor might be designed to not "alarm" until several consecutive unacceptable corrections were broadcast, thus multiplying the warning time. This is apparently not the case for either of the alternatives under consideration here.

The rationale for predicting the time to receive a warning of failure will be essentially the same as that for estimating the average age of a DGPS correction, as discussed above under "accuracy" [Ref. 16:p. 43]. Thus, about a 0.4 second advantage is expected for the radiobeacon alternative, which is barely significant here. A warning of an unusable satellite pseudorange should arrive within 10 seconds of its exceeding safe parameters to comply with the rigorous aviation non-precision approaches in the U.S. [Ref. 16:p. 27].

b. *Index of Safety*

This MOP takes into consideration the danger of the integrity mechanism failing altogether, and transmitting dangerously erroneous information. This MOP also considers protection against excessive false alarms. If an integrity monitor station fails, it is preferable that a coordinating station be available to assume the task of determining the point of failure and discarding the faulty input than to have the DGPS signals be declared unusable until the integrity mechanism may be repaired. This feature reduces the danger of the user community ignoring a proper alarm due to excessive previous false alarms. These considerations are dependent on the design of the reference station and integrity monitoring components, and are assumed to be identical for the alternatives considered here.

5. Adaptability

This FOM is an umbrella for several difficult-to-quantify objectives and considerations that were discussed in Chapter III. All look beyond the technical issues of the basic problem toward engineering a solution well-suited to adapting to future events.

a. International Compatibility

This consideration was discussed in Chapter III.B.2.a. Adherence to the RTCM "Recommended Standards for Differential NAVSTAR GPS Service" is assumed for any acceptable alternative, but the RTCM does not endorse any specific data broadcast method. However, some alternatives will tend to lead more directly to standardized, internationally compatible DGPS user equipment than others.

At the present time, radiobeacons seem to have the edge in this category. The RTCM document singles out MSK modulated MF radiobeacons as an attractive candidate. The IALA Radionavigation Technical Committee, Systems Working Group has reported "that maritime radiobeacons are the most suitable means of transmitting corrections in a coastal area" [Ref. 53:p. 6]. Also:

> Foreign efforts are now underway for other prototype DGPS services. The Swedish board of Shipping and the Finnish Board of Navigation are engaged in a joint effort to provide a marine radiobeacon-based DGPS service for the ferry systems which operate between Stockholm and Helsinki. The service will begin this Spring and the results will premiere at the September 1991 meeting of the IALA in Stockholm, Sweden. [Ref. 21:p. 6]

b. Interagency Compatibility

This objective was discussed in Chapter III.A.3 f. Corps of Engineers, FAA, DOD, and NOAA needs and initiatives may be better

complemented by a particular alternative. For example, the broadcast of decimeter-level DGPS information desired by the Corps of Engineers may be feasible on a satellite channel, but not on the radiobeacon MSK channel due to its limited data rate [Ref. 52:p. 2]. It would also be less difficult for a satellite-oriented Coast Guard DGPS network to provide integrity information for a satellite-based GIC, which FAA seems intent on implementing. Therefore, the satellite alternative seems to have an advantage.

c. *Technical Flexibility*

Modularity and considerations for future expansion should be designed into any DGPS system fielded, as discussed in Chapter III.B.1. Examples include provisions for multi-station DGPS solutions and expansion to other broadcast media, such as a public maritime data communications interface.

For both alternatives, the network can be designed quite well with these considerations in mind. However, the satellite alternative seems to be superior in this MOP due to its greater potential data rate. Also, if it is decided to shift to another medium altogether, the radiobeacon alternative would leave many users with obsolete DGPS user equipment sets; satellite equipment sets, on the other hand, would probably be partially usable for other satellite communication applications.

d. *Open Systems Interoperability*

This MOP does *not* refer to the broadcast of DGPS corrections in terms of the OSI reference model, but to the design and operation of the DGPS network itself. The considerations associated with this were discussed in Chapter

III.B.2.b. The DGPS network should consist of multi-vendor interoperable modules with standard interfaces. The system can be designed to satisfy these considerations equally well with either alternative.

e. Spectral Efficiency

This MOP has two aspects. As was noted in Chapter III.B.3, there are difficult and time consuming barriers to acquiring new spectrum allocations for data transmissions. Also, some implementations of DGPS service could interfere with existing services.

Neither of the alternatives we are analyzing would have a need to acquire additional spectrum utilization authorization. Fears that the MSK modulation scheme would interfere with certain aviation radiobeacon direction-finding equipment designs have not been confirmed [Ref. 21:p. 11]. Thus, both alternatives are considered equal with respect to this MOP.

f. Institutional Impact

One aspect of this MOP was discussed in Chapter III.A.3.g.: support of other radionavigation services. The synergy with the GPS civil liaison mission will be gained equally well with either DGPS implementation.

Mariners have become less likely to use radiobeacons for direction-finding in recent years, and significant savings could be had by eventually discontinuing their operation. The radiobeacon alternative has a negative impact upon the Coast Guard radionavigation program in that it may prohibit the phasing out of radiobeacons in the future. On the other hand, it is possible that this use of radiobeacons would pave the way for utilizing them for other data transmissions.

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As discussed in Chapter II.C.4, the RTCM standard has already reserved certain message types for exploration of multi-purpose data links.

Another aspect of this MOP relates to private sector participation in radionavigation services, as discussed in Chapter III.B.6. Companies desiring to provide radionavigation services to the public generally wish to do so with Coast Guard licensing and monitoring, so as to gain the some protection against liability in the event of a catastrophic failure. This places the government in a vulnerable position over which it would prefer to maintain full control. Additionally, such a government sponsored (but commercially provided) public service could be abruptly discontinued due to private sector financial difficulties beyond the government's control. Finally, it is probable that merchant vessel regulations will mandate the carrying of DGPS equipment; it would be undesirable to require the carrying of equipment designed to access a single company's service.

Assignment of utility to this MOP is very subjective; each alternative has a disadvantage in a different aspect. However, the satellite alternative is perceived to have the stronger overall disadvantage in this MOP.

6. FOM Calculations

After defining these measures, the CEA procedure calls for establishing MOP weights, assigning utilities, and calculating the FOM expected values [Ref. 65:pp. 9-10]. A weight and utility (zero to ten) have been assigned to each alternative relative to each MOP in Table 5-1. For each MOP, the radiobeacon alternative (the median alternative in this case) has been assigned a utility of five. The FOM expected values are computed in Table 5-1 and carried forward to Table

5-2, where they are weighted and totaled to determine the effectiveness totals. Risk for each alternative is considered in Chapter VI.

C.   DGPS COST ESTIMATION

Appendix A contains the computations for total present value life-cycle cost (including the public's user equipment) for each of the alternatives under consideration. The present value cost of the satellite alternative ($190.3 million) is estimated to be much higher than that of the radiobeacon alternative ($109.1 million). The cost disparity is primarily due to the impact of more expensive satellite user terminals.

The primary origin of the acquisition and operation cost figures is the March 1991 "Resource Prospectus" for the proposed DGPS. In accord with that source document:

- Four percent inflation is applied to project 1992 "Budget Year" dollar requirements. Subsequent years all assume 1992 dollars. Thus, "BY+1" indicates 1993 costs in 1992 dollars.

- Personnel costs are assumed to be $50,000 per individual. This is an average cost, which incorporates pay, benefits, and attributable institutional overhead.

1.   User Equipment

The anticipated 25 year life-cycle requires some difficult forecasts of user equipment cost and public demand. These estimates allow us to consider the relatively modest signal equipment acquisition costs against the perspective of much larger life-cycle costs.

Analogy with the previous radionavigation systems was the primary source for user equipment projections.

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The development and implementation of Loran-C, Omega, and more recently, GPS follow along similar paths... a competitive market supported by numerous, mostly small companies materializes, and the quantity of receivers sold increases with a corresponding drop in price.... [Ref. 73:p. 43]

It has been assumed that these patterns may also be extended to DGPS. The graphs illustrating Loran-C's history given by Beukers [Ref. 73:p. 43] provide a guide for the trends to be assumed for DGPS user equipment in the cost spreadsheets (Appendix A). Figures 5-4 and 5-5 are adapted from this source. However, Appendix A assumes that user equipment prices level out at $100 per set.

Other sources support recognition of these trends, as well. The 1983 "NAVSTAR GPS Simulation and Analysis Program" report prepared by the Transportation Systems Center draws on existing cost studies to project costs of GPS receivers 18 years into the future.

To a first approximation, each trend can be characterized by a period of time whereby the subcomponent price is cut in half, called the "cost-halving" time. [Ref. 74:p. 9-4]

The report also notes that receivers will use more digital and fewer analog components over time, and cites a 3.5 to 5.0 year cost-halving period for digitally oriented civil navigation components [Ref. 74:p. 9-4, E-6]. The Loran case history is within the lower end of this span. Appendix A therefore is considered reasonably conservative in its use of a 4.0 year cost-halving period for DGPS receivers of both types; this coincides fairly well with Beukers' Loran graph over the relevant range.

Determining a starting point from which to apply this model required the author to make some subjective evaluations. It was found that forecasts of
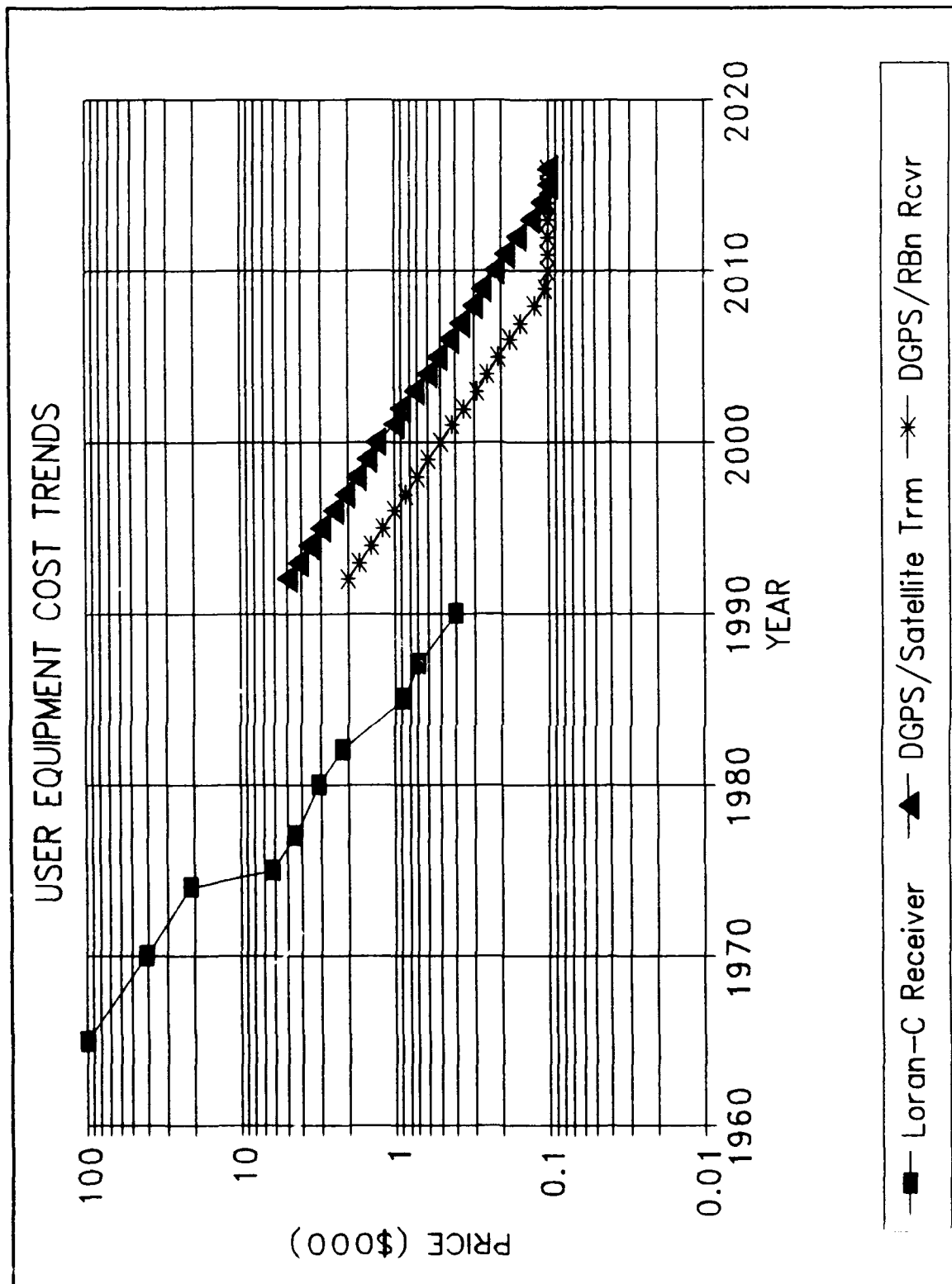
Figure 5-4. User Equipment Cost Trends [after Ref. 73]

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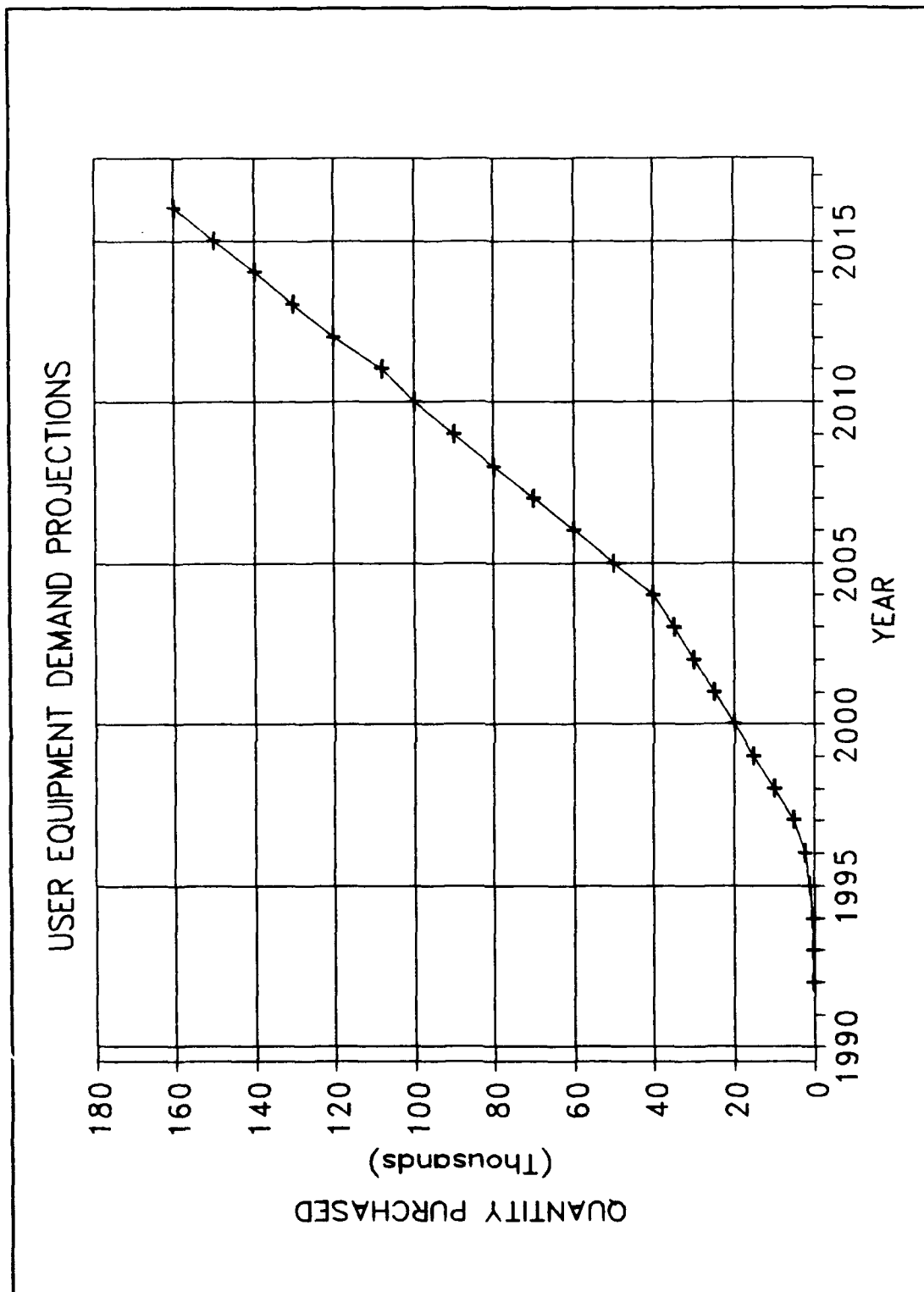
Figure 5-5. User Equipment Demand Projections
[after Ref. 73]

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prices for each type of DGPS reception equipment varied widely among experts in the field. This aspect of the CEA model should certainly be re-evaluated as market prices mature.

a. DGPS/Radiobeacon Receiver Price

In April 1991 Magnavox quoted a price of $6,800 for a MX-50R Radiobeacon MSK receiver. This price was deemed to be too early to serve as the origin of the cost-halving trend just described. Referring to the Loran-C analogy, one should note that there was a significant drop in user set price in 1975. This took place after Loran-C was declared the official radionavigation system for U.S. coastal waters. A similar drop is probable for Radiobeacon MSK DGPS equipment prices should that alternative be officially adopted.

Instead of extrapolating directly from this known price, four knowledgeable industry observers were interviewed and provided 1996 price forecasts. Each expert's "best guess" was between $2000 and $400. The author has selected $1000 to proceed with the analysis. This price estimate includes manufacturer and distributor overhead, in addition to cost of parts. It is used to define the starting point for plotting price trend as a straight line on "log-lin" graph paper. Cost and demand projections actually used are illustrated graphically in Figures 5-4 and 5-5. [Ref. 73:pp. 42-47]

b. DGPS/AMSC Satellite User Terminal Price

AMSC representatives stated that user equipment is still under development. However, they anticipate a market price of $2000 for land-mobile voice terminals when produced in volume [Ref. 62]. Other knowledgeable industry

observers estimated that this type of DGPS receiver will have a parts-count four to ten times that of the $1000 (estimated) radiobeacon MSK receiver. The author estimates a price of $2500 for a marine unit adapted for the DGPS data link function in 1996.

2.   Operation Cost

No forecasts of fees for continuous DGPS broadcasts were available from AMSC as of this writing; the satellite broadcast fees cited here [Ref. 52:p. 604] could not be confirmed. This adds considerable risk to the satellite alternative cost projections in Chapter VI.

Previous cost analyses show that electronics labor costs will tend to rise, offsetting declining digital component costs [Ref. 74:p. 9-4]. Continuing maintenance and operating costs are deemed to be more labor oriented, so cost-halving trends applied to user costs have not been applied to the operating costs in Appendix A.

3.   Present Value Cost

When costs are distributed over time, economic theory dictates that the time value of money be considered. A monetary cost in the future is multiplied by a discount factor to yield its present value, as discussed in Section A of this chapter. Present value cost over time for each alternative is illustrated in Figure 5-6. The relative sizes of service acquisition (i.e., Coast Guard implementation costs), service operation, and user equipment total present value costs for each alternative are listed in Table 5-3 and illustrated in Figure 5-7.

Table 5-3. Cost Breakdown Categories: Life-Cycle Cost ($M)

	Radiobeacon	Satellite
User Equipment ($M)	58.8	134.6
Service Operation ($M)	40.0	47.9
Acquisition ($M)	10.3	7.8
Total PV Cost ($M)	109.1	190.3

4. Component Cost Estimations

Several cost estimations in Appendix A were made with the best information available to the author as of this writing, but are very likely to become firmer in the near future. These include:

- User equipment costs and demands.

- Earth station interface cost. It has been assumed that the Coast Guard would not purchase earth stations in the interest of future flexibility.

- System architecture. It has been assumed that the cost of establishing and maintaining redundant connectivity from necessary Coast Guard operated components to the AMSC earth station would be equal to that of connectivity between the 44 radiobeacons and other system components. It has also been assumed that integrity monitor costs are equivalent.

- Satellite channel capacity broadcast cost. The broadcast fees cited here are in the process of being re-evaluated by AMSC as of this writing [Ref. 52:p. 604].

- Satellite facility regulation. Governmental oversight cost is the author's estimate.

- New radiobeacon installation and operating costs. This will vary significantly according to final system configuration and the remoteness of the sites.

- USCG operating personnel costs. These estimations pessimistically assume a low degree of control station automation and no cross-utilization of existing Coast Guard unit personnel. However, any resulting inaccuracies are applied equally to both alternatives, since radiobeacons are unmanned facilities.
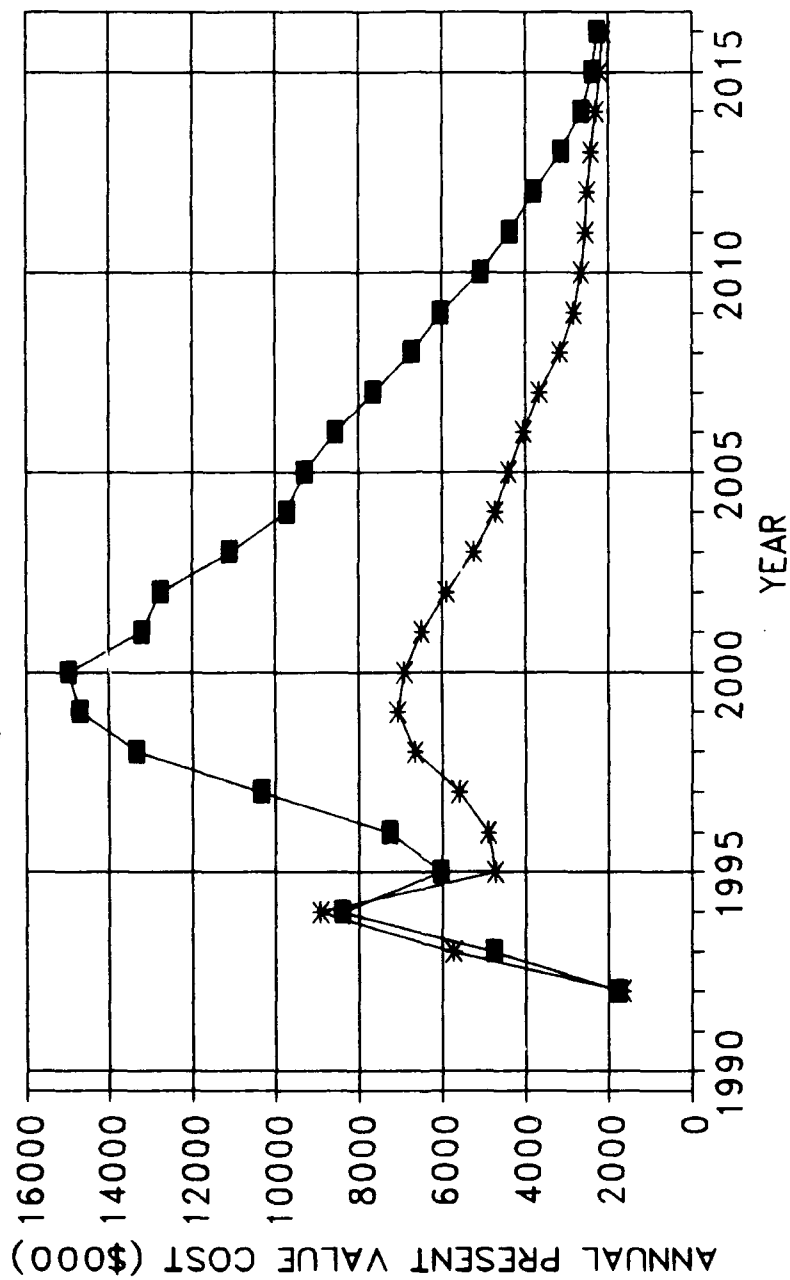
Figure 5-6. Present Value Total Cost over Time

Total Present Value Cost Breakdown
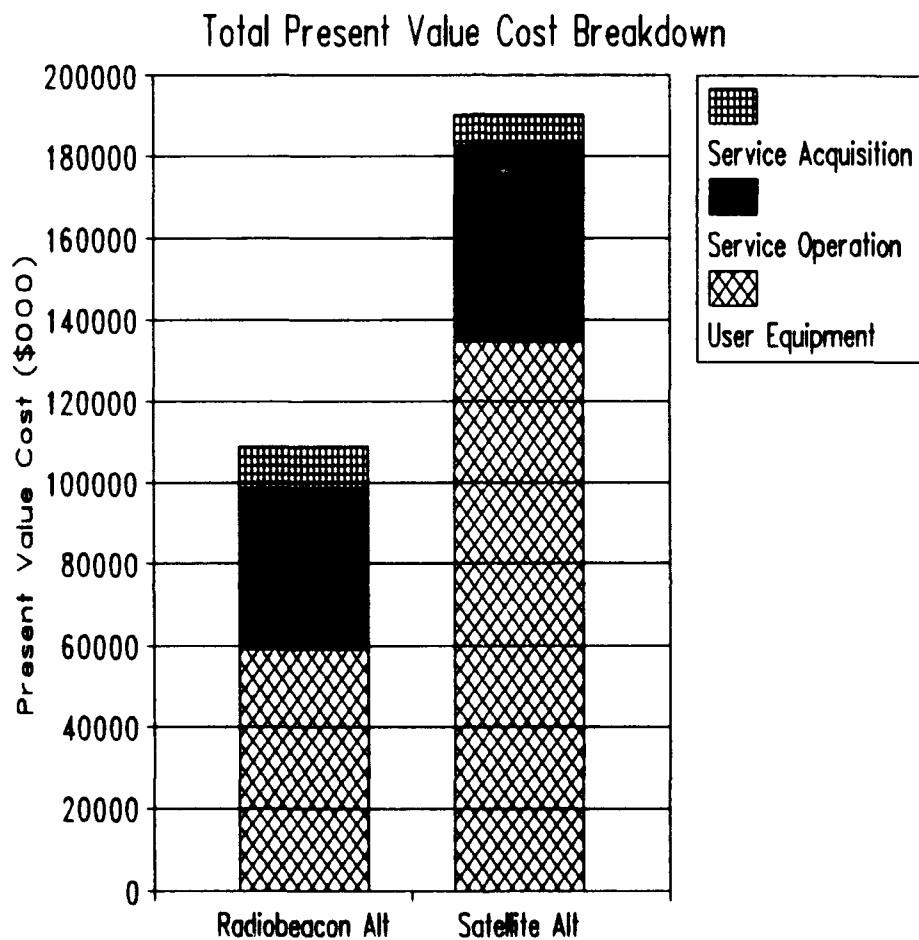
Figure 5-7. Breakdown of Present Value Costs by Category

VI. ANALYSIS

A. RISK

"Risk" is used here to mean the size of the probability distribution about an expected value. The uncertainties (risks) associated with the effectiveness and life-cycle cost estimates for each alternative are different, depending on the author's confidence in the forecasts used to make the estimates. Once these risks are assessed, they are displayed by plotting the statistical confidence interval ("2 sigma", or 95% is used here) about the expected value on each axis of the Cost-Effectiveness (C-E) graph. The realm of possibility defined by the ellipse around any alternative is a good representation of its risk in each dimension. In this case, large risks will weigh heavily against an alternative due to the need to field a DGPS system quickly.

1. Effectiveness Risk

Basically, effectiveness risk is proportional to the maturity of the technology associated with each MOP in Table 5-1. For example, research needs to be done to ascertain each alternative's resistance to manmade electromagnetic interference in the harbor environment (see Chapter V.B.2.b). Effectiveness risk also incorporates the possibility that an alternative may eventually fail to be feasible at all; this might be considered "overall" risk, which is difficult to assign to any one MOP or FOM, but may be considered in aggregate here.

The author has assigned the radiobeacon alternative an effectiveness risk of ± 0.4 (95% confidence interval). The radiobeacon alternative has a proven

Coast Guard prototype, as well as an operational system in Scandinavia. It is almost certain that a system meeting the minimum requirements of Chapter IV can be implemented before 1996. However, the integrity safeguards necessary to meet the requirements specified in Chapter IV have not yet been demonstrated. There is also some question on how the remote location of many of the radiobeacon sites will impact availability. Data links and power supplies may be unreliable at difficult sites.

The author has assessed the satellite alternative's effectiveness risk to be ± 1.2 (95% confidence interval); this is approximately three times as great as that of the radiobeacon alternative. Although other satellite companies have successfully proven the viability of mobile-user satellite communications systems, no AMSC communications satellites will be launched before 1994. Space programs have a history of schedule difficulties, well illustrated by the delays in GPS satellite launches due to the space shuttle accident. In dealing with any commercial communications provider, delays or difficulties might also arise due to spectrum allocation disputes, or to financial difficulties beyond the control of the Coast Guard. AMSC's arrangement with the Canadian company TMI to provide redundant capacity and AMSC's willingness to provide adequate ground station redundancy are other effectiveness risk factors beyond the Coast Guard's control.

2. Cost Risk

This measure quantifies the probability that the cost of the DGPS service will be greater or less than expected. Both alternatives share a similar degree of cost risk for acquisition of common system components and operating

personnel costs, as discussed in Chapter V.C.4. For example, USCG operating personnel costs estimations pessimistically assume a fairly low degree of automation and no cross-utilization of existing unit personnel; actual implementation may allow for significant savings in this category.

The author has assigned the radiobeacon alternative a cost risk of ± 20% of the estimated present value life-cycle cost (95% confidence interval), including factors common to both alternatives. This is approximately $21.8 million. The majority of this risk is due to DGPS/radiobeacon user equipment cost; this is due to its relative size in comparison to total cost (see Figure 5-7) and to the long range forecasts required for the life-cycle model (as discussed Chapter V.C.1.a.). Satisfactory units are currently in production, but market prices are changing rapidly. The DGPS/radiobeacon alternative's service acquisition and operation cost estimates are deemed to be fairly good. However, new radiobeacon installation and operating costs may increase significantly if the necessary availability can not be obtained using existing remote radiobeacon sites.

The author has assessed the satellite alternative's cost risk to be ± 25% of the estimated present value life-cycle cost (95% confidence interval); this is approximately $47.6 million. Again, the majority of this risk is due to user equipment. AMSC user equipment prices and leased channel fees are forecast without the benefit of current market prices. In addition, it is not certain that the Coast Guard can win the use of free channel capacity as described in Chapter IV.D.1. The satellite broadcast fees cited in past literature could not be confirmed or updated by AMSC. Satellite facility regulation and oversight burden costs are

the author's estimates; in actuality, they would depend on the organizational relationship developed during implementation.

B.   COST-EFFECTIVENESS

Overall effectiveness and life-cycle costs were evaluated in Chapter V. Now that risks have been estimated, we have all the information necessary to construct the planar cost-effectiveness graph as described in Chapter V.A.8. Numerical results are summarized in Table 6-1. The resulting ratio represents the effectiveness per dollar of life-cycle cost. Since the effectiveness is measured in artificially generated units that are very small compared to costs, the ratios for both alternatives have been normalized by dividing by the radiobeacon alternative's effectiveness-to-cost ratio.

Table 6-1. Numerical Cost-Effectiveness Summary

	Radiobeacon	Satellite
Overall Effectiveness	5.0	4.835
Effectiveness Risk	± 0.4	± 1.2
Life-Cycle Cost ($000)	109148	190290
Cost Risk ($000)	± 21830	± 47572
Normalized Cost-Eff Ratio	1.0	0.55

In this case, it appears that the satellite alternative is drastically more expensive, and slightly less effective than the radiobeacon alternative. Therefore, the radiobeacon alternative is almost twice as cost-effective. The planar cost-effectiveness graph of Figure 6-1 illustrates the differences. Effectiveness and cost

risks have been joined to form ellipses around the plotted alternatives. The slopes of the lines drawn from the origin to the alternatives show the C-E ratios.
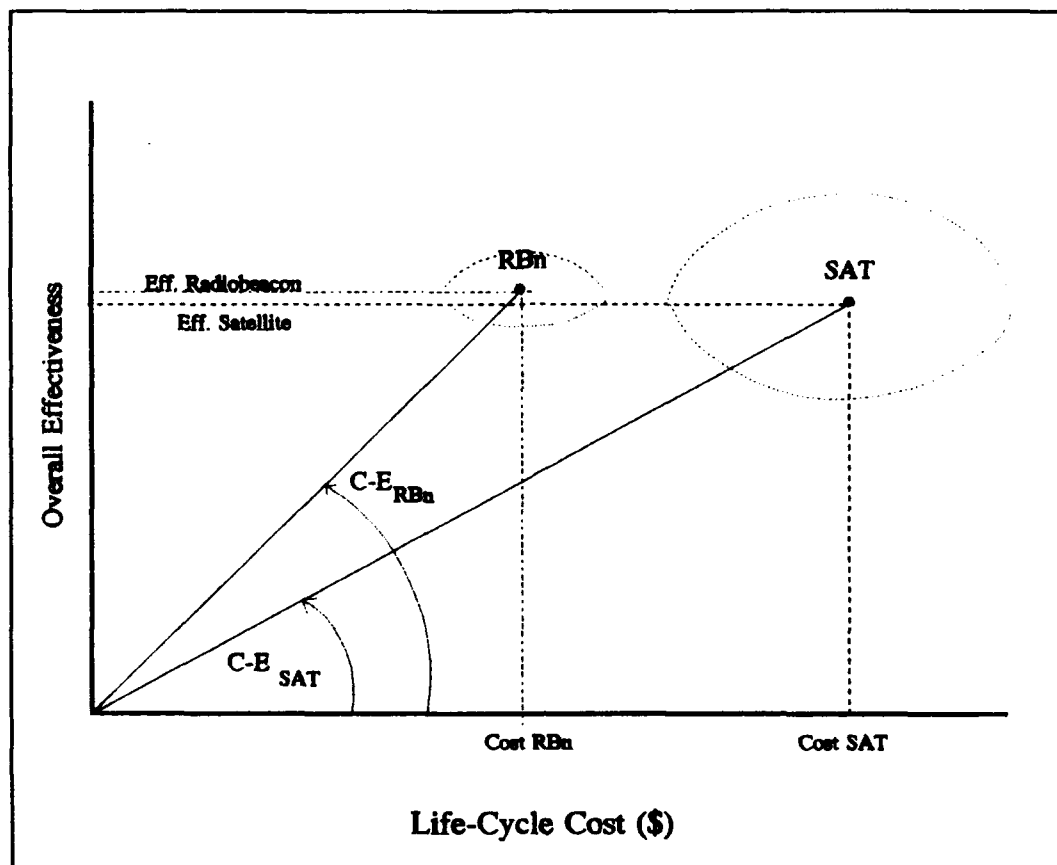
Figure 5-1. Graphical Cost-Effectiveness Comparison of Radiobeacon and Satellite Alternatives

C. SENSITIVITY ANALYSIS

The goal of this step is to identify those areas in which relatively minor changes in parameters could change or bar the finding of an "optimal" alternative. Several variations on the fundamental model discussed in the previous sections are of interest. It was found that there are some variations that could bring the two

alternatives closer together, but that no one reasonable variation would reverse the finding. The following scenarios are discussed below:

- Assume equal user equipment costs

- Assume a shorter life-cycle

- Omit user equipment costs from consideration

- Assume a different user equipment cost trend and market demand curve

- Omit present value costing

- Assume different FOM weights in computing effectiveness

1. Equal User Equipment Costs

The cost difference between the two types of user equipment is a decisive factor in the finding that the radiobeacon-based system is the more cost-effective alternative. The analyst could not make a confident selection (based on cost-effectiveness alone) were user equipment costs assumed to be equal.

During preliminary research for this thesis, initial user set costs were estimated without the benefit of the expert technical opinions cited in Chapter V.C.1. It was found that these preliminary forecasts of prices and demands for the two types of DGPS reception equipment were so close that it was not reasonable to differentiate between their expected values. For this variation, a 1991 $7,000 radiobeacon MSK receiver was used to define the starting point for plotting this trend as a straight line on "log-lin" graph paper (e.g., 1996 price estimated at $3000). AMSC representatives could not initially provide a current price estimate, so estimated user equipment costs were extrapolated from the 1987/1988 AMSC filings with the FCC [Ref. 57:p. 136]. This put the 1996 cost reasonably close to

the radiobeacon MSK receiver's, although the satellite receiver would have a *much greater risk* associated with its cost projections.

Table 6-2 indicates the overall results of equating user equipment cost at $3000 in 1996 for both alternatives.

Table 6-2. Cost-Effectiveness Summary: Equal User Costs

	Radiobeacon	Satellite
Overall Effectiveness	5.0	4.835
Life-Cycle Cost ($000)	210222	215639
Normalized Cost-Eff Ratio	1.0	0.94

Cost risk would be considerably higher than in Table 6-1 for both alternatives in this scenario. The cost-effectiveness distinction between the alternatives would be insignificant in comparison to the "noise" induced by the vagueness of the cost estimates. However, the radiobeacon alternative would still retain a significant advantage of having a lower effectiveness risk.

2. Shorter Life-cycle

It is reasonable to speculate that whatever DGPS broadcast medium is selected now, it could be made obsolete by new policy and technology before the end of its projected 25 year life-cycle. Cost-effectiveness would be changed somewhat in such an occurrence, but not enough to change the finding. Table 6-3 interrupts the cost model in the year 2000 (BY+8); Table 6-4 does the same in the year 2005 (BY+13).

Table 6-3. Cost-Effectiveness Summary: End Service Year 2000

	Radiobeacon	Satellite
Overall Effectiveness	5.0	4.835
Life-Cycle Cost ($000)	52059	81605
Normalized Cost-Eff Ratio	1.0	0.62

Table 6-4. Cost-Effectiveness Summary: End Service Year 2008

	Radiobeacon	Satellite
Overall Effectiveness	5.0	4.835
Life-Cycle Cost ($000)	78771	137738
Normalized Cost-Eff Ratio	1.0	0.55

3. Omit User Equipment Costs

The Federal Radionavigation Plan states that analysis should consider user equipment as part of system cost [Ref. 9:p. 1-26]. However, the cost-effectiveness values would be greatly affected by ignoring this mandate and considering only the cost to the service provider, as shown in Table 6-5.

Table 6-5. Cost-Effectiveness Summary: Omit User Equipment

	Radiobeacon	Satellite
Overall Effectiveness	5.0	4.835
Life-Cycle Cost ($000)	50330	55748
Normalized Cost-Eff Ratio	1.0	0.87

The cost-effectiveness distinction between the alternatives would not be as significant as in the foundation analysis. Risk estimates have not been quantified for this sensitivity analysis; however, the risk associated with the cost

and effectiveness estimates probably would cause the ellipses plotted on the cost-effectiveness graph to overlap. Regardless, the radiobeacon alternative would retain the significant advantage of having a lower effectiveness risk.

4. Different User Equipment Cost/Demand Curves

Changing the user equipment cost-halving rate or modifying the demand curves illustrated in Figures 5-4 and 5-5 would change the relative costs of user equipment in proportion to other expenses. As seen in the previous paragraphs, increasing the proportional cost of user equipment will accentuate the finding in favor of the radiobeacon alternative. Decreasing this proportion blurs the distinction, but does not reverse the finding.

5. Omit Present Value Costing

OMB circular A-94 prescribes the discounting technique discussed in Chapter V.A.6.c. [Ref. 72]. Omitting this procedure would make the costs incurred in the operations and user equipment categories proportionally more expensive than in the foundation scenario. However, this does not alter the choice of alternative, as shown in Table 6-6.

Table 6-6. Cost-Effectiveness Summary: Omit P.V. Costing

	Radiobeacon	Satellite
Overall Effectiveness	5.0	4.835
Life-Cycle Cost ($000)	340404	589546
Normalized Cost-Eff Ratio	1.0	0.56

6. Different FOM Weights

Table 5-2 used the FOM weights as perceived by the author to make its overall effectiveness evaluation in favor of the radiobeacon alternative. "Coverage" is the only FOM in which the satellite alternative enjoys an advantage. If this criterion were to take on much greater weight, and availability and integrity were de-emphasized, then the satellite alternative would receive a higher effectiveness rating than the radiobeacon alternative. However, even by increasing this FOM to ten and reducing all others to five, the overall effectiveness would be only 5.14, compared to 5.0 for the radiobeacon alternative. See Table 6-7: this hypothetical effectiveness advantage could not overcome the tremendous cost disadvantage imposed by user equipment cost, as forecast by the foundation model. This variation would merit re-evaluation in the event that the market price of DGPS/AMSC satellite user equipment were to prove equal to the price of the alternative, as discussed in paragraph 1.

Table 6-7. Cost-Effectiveness Summary: Vary FOM Weights

	Radiobeacon	Satellite
Overall Effectiveness	5.0	5.14
Life-Cycle Cost ($000)	109148	190290
Normalized Cost-Eff Ratio	1.0	0.59

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VII. CONCLUSIONS

In this study, the author consolidates the discussion of key Differential Global Positioning System (DGPS) issues within one document, considers the cost-effectiveness analysis process, identifies DGPS technical decision criteria, estimates alternative system costs, and executes a comparison of two DGPS service alternatives. The primary conclusions relate to the need for DGPS service, the applicability of cost-effectiveness analysis, the identification of effectiveness criteria, and the preliminary finding that a radiobeacon-based system is preferable to one based on a dedicated satellite channel.

A. NEED FOR DGPS SERVICE

The Coast Guard DGPS service initiative is an innovative and worthwhile program that addresses an emerging national need for extremely high navigational accuracy. One of the Coast Guards's missions is to establish and operate electronic aids to navigation to prevent disasters and serve the needs of the maritime commerce of the U.S. DGPS has the potential to provide an unprecedented capability for radionavigation in restricted waters, particularly if it is integrated with real-time display on electronic charts. This combination could allow higher vessel safety or economic efficiency in harbors, especially in darkness or unfamiliar ports. DGPS-level accuracy is also needed for the Coast Guard's own use to perform its missions most efficiently. The Coast Guard is well suited to provide

DGPS service, since it can build on the experiences of its other radionavigation systems.

B. COST-EFFECTIVENESS ANALYSIS

Cost-effectiveness Analysis (CEA) is an economic analysis tool suitable for performing systems engineering during the design of a DGPS service. This method is essentially a means of quantifying effectiveness per dollar of cost. It allows consideration of the elements of the system on an integrated basis. The effectiveness model quantifies the various performance trade-offs to allow optimization of system design. The cost analysis portion of the CEA provides a structure for the inclusion of life-cycle costs, including user equipment (as required by Federal policy).

The model, in itself, is not the decision maker, but a tool that presents the necessary data in support of the decision-making process. It allows various parties to a decision to observe the basis for each other's conclusion. Instead of supplying an immediate answer, the CEA model may aid the evolution of a DGPS service design by facilitating iterative systems engineering to *gradually* produce an optimal solution. This CEA model is especially suited to decision making in an environment of technological and policy change, since it can be easily refined and updated over the predicted four-year implementation period.

The essential steps of cost-effectiveness analysis adapted for DGPS implementation planning are:

- define system objectives (Chapter III)
- state evaluation assumptions (Chapter III)

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- identify essential mission requirements (Chapter IV)

- list alternatives (Chapter IV)

- establish effectiveness measures (Chapter V)

- evaluate alternatives' overall effectiveness (Chapter V)

- develop cost data (Chapter V)

- assess effectiveness and cost risks (Chapter VI)

- perform cost-effectiveness computations (Chapter VI)

- perform sensitivity analysis (Chapter VI)

C.   DGPS DECISION/SELECTION CRITERIA

The structure for analyzing the effectiveness of a DGPS system is proposed in Chapter V.B., and illustrated in Tables 5-1 and 5-2. This model is a simplified representation of the real world, which is adapted to abstract the features of the problem being analyzed. It is designed to compare the effectiveness of alternatives satisfying the fundamental system requirements. This is done using a hierarchical weighting scheme: several "elemental" Measures Of Performance (MOP's) are weighted and summed to produce one Figure Of Merit (FOM). All of the system FOM's are weighted and summed to produce the overall system effectiveness. The relative weights (contributions) of MOP's to each FOM, and FOM's to overall effectiveness should be assigned before any rating is done. This helps to avoid the inadvertent inclusion of personal bias in the model.

The analysis of DGPS technology, objectives, assumptions and considerations, and requirements lays the foundation for the selection of effectiveness criteria;

these are called MOP's and FOM's in the model. MOP's are grouped by the FOM
they contribute to as follows:

- Accuracy: update rate, latency, reference station spacing

- Availability: component dependability, resistance to EMI, resistance to
  ionospheric variations, resistance to multipath and signal obstruction,
  graceful degradation

- Coverage: harbor and harbor approaches and coastal phase, ocean phase,
  inland phase

- Integrity: timeliness, index of safety

- Adaptability: international compatibility, interagency compatibility, technical
  flexibility, open systems interoperability, spectral efficiency, institutional
  impact.

D. COMPARISON OF SELECTED ALTERNATIVES

The preliminary findings of this thesis indicate that a system using

radiobeacon broadcast nodes is preferable over satellite-based system. In this case,

it appears that the satellite alternative is drastically more expensive, and slightly

less effective than the radiobeacon alternative. Therefore, the radiobeacon

alternative is almost twice as cost-effective. Also, the larger risks associated with

the satellite alternative weigh against it, due to the need to field a DGPS system

quickly. However, these CEA results are based upon the author's necessarily

subjective weighting and rating of the two systems' performance parameters and

preliminary cost information. Only these two system configurations were

considered.

The effectiveness and cost risk analysis indicate a high level of confidence in

this finding; the "realm of possibility" ellipses in Figure 6-1 do not overlap.

Furthermore, sensitivity analysis shows this conclusion to be quite robust in the face of other changes in the model. No areas have been found in which relatively minor changes in parameters could reverse the finding of an "optimal" alternative. It was found that there are some variations that could bring the two alternatives close together, but no one reasonable variation would reverse the finding.

User equipment prices are the primary factor in the total life-cycle cost of DGPS service alternatives considered here. About 53% of the DGPS/radiobeacon alternative total cost was attributable to user radiobeacon receiver equipment. About 71% of the DGPS/AMSC satellite alternative cost was attributable to user satellite terminal equipment. It is important to foster innovation and price competition among commercial manufacturers in order to minimize DGPS user equipment prices. This will encourage widespread public use of a beneficial, safety-oriented service.

APPENDIX A. COST COMPUTATIONS

COST ESTIMATE FOR RADIOBEACON ALTERNATIVE

ACQUISITION	BY	BY+1	BY+2	BY+3	BY+4	TOTAL
USCG SIGNAL EQP	1450	3522	4895	0	0	9867
PERSONNEL(16)	100	869	597	326		1892
INVESTMENT COST	1550	4391	5492	326	0	11759

OPERATION	BY	BY+1	BY+2	BY+3	BY+4	BY+5	BY+6	BY+7	BY+8	BY+9	BY+10
USCG OPER CSTG		326	1288	1288	1288	1288	1288	1288	1288	1288	1288
PERSONNEL(64)	50	1304	3476	3476	3476	3476	3476	3476	3476	3476	3476
SERV OPER. COST	50	1630	4764	4764	4764	4764	4764	4764	4764	4764	4764
NEW RDCST RCVRS	20	150	400	1000	2400	5000	10000	15000	20000	25000	30000
SINGLE SET COST	2	1.7	1.42	1.19	1	0.84	0.7	0.6	0.5	0.42	0.35
TOTAL RCVR COST	40	255	568	1190	2400	4200	7000	9000	10000	10500	10500
ANNUAL TOTALS	1640	6276	10824	6280	7164	8964	11764	13764	14764	15264	15264
Years After BY	0	1	2	3	4	5	6	7	8	9	10
Discount Factor	1	0.9091	0.8264	0.7513	0.6330	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855
Present Val Cost	1640	5705	8945	4718	4893	5566	6640	7063	6888	6473	5885

COST ESTIMATE FOR RADIOBEACON ALTERNATIVE

ACQUISITION	BY+11	BY+12	BY+13	BY+14	BY+15	BY+16	BY+17	BY+18	BY+19	BY+20	BY+21
USCG SIGNAL EQP											
PERSONNEL (16)											
INVESTMENT COST											
OPERATION	BY+11	BY+12	BY+13	BY+14	BY+15	BY+16	BY+17	BY+18	BY+19	BY+20	BY+21
USCG OPER COSTS	1288	1288	1288	1288	1288	1288	1288	1288	1288	1288	1288
PERSONNEL (64)	3476	3476	3476	3476	3476	3476	3476	3476	3476	3476	3476
SERV OPER. COST	4764	4764	4764	4764	4764	4764	4764	4764	4764	4764	4764
NEW RCGST RCVRS	35000	40000	50000	60000	70000	80000	90000	100000	108000	120000	130000
SINGLE RET COST	0.29	0.25	0.21	0.175	0.15	0.123	0.105	0.1	0.1	0.1	0.1
TOTAL USER COST	10150	10000	10500	10500	10500	9840	9450	10000	10800	12000	13000
ANNUAL TOTALS	14914	14764	15264	15264	15264	14604	14214	14764	15564	16764	17764
Years After BY	11	12	13	14	15	16	17	18	19	20	21
Discount Factor	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486	0.1351
Present Val Cst	5227	4704	4421	4019	3654	3178	2812	2655	2545	2492	2400

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COST ESTIMATE FOR RADIOBEACON ALTERNATIVE

ACQUISITION	BY+22	BY+23	BY+24	TOTAL
USCG SIGNAL EQP				9867
PERSONNEL(116)				1892
INVESTMENT COST				11759

OPERATION	BY+22	BY+23	BY+24	TOTALS
USCG OPER COSTG	1288	1288	1288	29950
PERSONNEL(64)	3476	3476	3476	81302
SERV OPER. COST	4764	4764	4764	111252
NEW LDCST RCVRS	140000	150000	160000	1441970
SINGLE SET COST	0.1	0.1	0.1	
TOTAL USER COST	14000	15000	16000	217393
ANNUAL TOTALS	18764	19764	20764	340404
Years After BY	22	23	24	
Discount Factor	0.1228	0.1117	0.1015	
Present Val Cst	2305	2207	2108	109148

COST ESTIMATE FOR SATELLITE ALTERNATIVE

ACQUISITION	BY	BY+1	BY+2	BY+3	BY+4	TOTAL
USCG SIGNAL EQP	1450	3522	4895			9867
PERSONNEL(16)	100	869	597	326		1892
EARTH STA INTFC		61	61			122
Less FED EQP:						
REG's,UPGD,GP		-1467	-1468			-2935
RED COMS INST		-61	-61			-122
INVESTMENT COST	1550	2924	4024	326		8824

OPERATION	BY	BY+1	BY+2	BY+3	BY+4	BY+5	BY+6	BY+7	BY+8	BY+9	BY+10
USCG OPER COSTS		326	1288	1288	1288	1288	1288	1288	1288	1288	1288
PERSONNEL(64)	50	1304	3476	3476	3476	3476	3476	3476	3476	3476	3476
SAT CHNL CAPAC	0	0	0	0	0	1470	1470	1470	1470	1470	1470
SAT FACIL REG.	50	50	50	50	50	50	50	50	50	50	50
Less:											
OLD RED INCR			-10	-20	-30	-33	-33	-33	-33	-33	-33
NEW RED's OF			-60	-110	-110	-110	-110	-110	-110	-110	-110
SERV OPER. COST	100	1680	4744	4684	4674	6141	6141	6141	6141	6141	6141
NEW EDCST RCVRS	20	150	400	1000	2400	5000	10000	15000	20000	25000	30000
SINGLE SET COST	5	4.2	3.55	3	2.5	2.1	1.75	1.5	1.3	1	0.9
TOTAL EDSR COST	100	630	1420	3000	6000	10500	17500	22500	26000	25000	27000
ANNUAL TOTALS	1750	5234	10188	8010	10674	16641	23641	28641	32141	31141	33141
Years After BY	0	1	2	3	4	5	6	7	8	9	10
Discount Factor	1	0.9091	0.8264	0.7513	0.6830	0.6209	0.5645	0.5132	0.4665	0.4241	0.3855
Present Val Cst	1750	4758	8420	6018	7290	10333	13345	14697	14994	13207	12777

COST ESTIMATE FOR SATELLITE ALTERNATIVE

ACQUISITION	BY+11	BY+12	BY+13	BY+14	BY+15	BY+16	BY+17	BY+18	BY+19	BY+20	BY+21
USCG SIGNAL EQP											
PERSONNEL(16)											
EARTH STA INTFC											
Less NBD EQP:											
RED'e, UPGD, SP											
RED COMS INST											
INVESTMENT COST											
OPERATION											
USCG OPER COSTS	1288	1288	1288	1288	1288	1288	1288	1288	1288	1288	1288
PERSONNEL(64)	3476	3476	3476	3476	3476	3476	3476	3476	3476	3476	3476
SAT CHNL CAPAC	1470	1470	1470	1470	1470	1470	1470	1470	1470	1470	1470
SAT FACIL PRS.	50	50	50	50	50	50	50	50	50	50	50
Less:											
OLL PRD INCR	-33	-33	-33	-33	-33	-33	-33	-33	-33	-33	-33
NEW PRD's OP	-110	-110	-110	-110	-110	-110	-110	-110	-110	-110	-110
SERV OPER. COST	6141	6141	6141	6141	6141	6141	6141	6141	6141	6141	6141
NEW HDCST RCVRS	35000	40000	50000	60000	70000	80000	90000	100000	108000	120000	130000
SINGLE SET COST	0.73	0.61	0.52	0.44	0.37	0.31	0.27	0.22	0.19	0.16	0.13
TOTAL USER COST	25550	24400	26000	26400	25900	24800	24300	22000	20520	19200	16900
ANNUAL TOTALS	31691	30541	32141	32541	32041	30941	30441	28141	26661	25341	23041
Years After BY	11	12	13	14	15	16	17	18	19	20	21
Discount Factor	0.3505	0.3186	0.2897	0.2633	0.2394	0.2176	0.1978	0.1799	0.1635	0.1486	0.1351
Present Val Cst	11108	9731	9310	8569	7670	6734	6023	5061	4359	3767	3114

COST ESTIMATE FOR SATELLITE ALTERNATIVE

ACQUISITION	BY+22	BY+23	BY+24	TOTALS
USCG SIGNAL EQP				9867
PERSONNEL(16)				1892
EARTH STA INTFC				122
Less R&D EXP:				
R&D's, UPGD, GP				-2935
R&D COES INST				-122
INVESTMENT COST				8824

OPERATION	BY+22	BY+23	BY+24	TOTALS
USCG OPER COSTS	1288	1288	1288	29950
PERSONNEL(66)	3476	3476	3476	81302
SAT CNRL CAPAC	1470	1470	1470	29400
SAT FACIL RES.	50	50	50	1250
Less:				
OLD R&D INCR	-33	-33	-33	
NEW R&D's OP	-110	-110	-110	
SERV OPER. COST	6141	6141	6141	138702
NEW EDCST RCVRS	140000	150000	160000	1441970
SINGLE SET COST	0.11	0.1	0.1	
TOTAL USER COST	15400	15000	16000	442020
ANNUAL TOTALS	21541	21141	22141	589546
Years After BY	22	23	24	
Discount Factor	0.1228	0.1117	0.1015	
Present Val Cst	2646	2361	2248	190290

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LIST OF REFERENCES

1. Blanchard, B.S., *Engineering Organization and Management*, Prentice-Hall, 1976.

2. U.S. *Code*, Title 14, "Coast Guard", sec. 81.

3. U.S. Coast Guard, *Resource Change Proposal for Differential GPS Navigation System*, RCP#285.05, Commandant (G-NRN), Washington, DC, 13 April 1990.

4. Mandler, M.B., Smith, M.W., and Gynther, J.W., "Precision Electronic Navigation in Restricted Waterways," *Navigation*, v.37, n.4, Winter 1990-91.

5. Bragaw, L.K., *Managing a Federal Agency: The Hidden Stimulus*, Johns Hopkins University Press, 1980.

6. Cook, W.J., "An Easy Way Out of This Mess," *U.S. News and World Report*, June 25, 1990.

7. RTCM Special Committee No. 104, *RTCM Recommended Standards for Differential NAVSTAR GPS Service*, Version 2.0, Washington, DC, January 1990.

8. Scull, D.C., "Future Scenarios for International Satellite Navigation and Positioning," *Proceedings of 5th International Geodetic Symposium on Satellite Positioning*, v.I., Defense Mapping Agency, Rockville, MD, March 1989.

9. Department of Defense and Department of Transportation DOD-4650.4/DOT-TSC-RSPA-88-4, *1988 Federal Radionavigation Plan*, December 1988.

10. NATO Team, NAVSTAR GPS Joint Program Office, *Introduction to NAVSTAR GPS User Equipment*, June 1987.

11. Wells, D., and Kleusberg, A., "GPS: A Multipurpose System," *GPS World*, v.1, n.1, January/February 1990.

12. Langley, R.B., "The GPS Receiver: An Introduction," *GPS World*, v.2, n.1, January 1991.

13. Lecture of Prof. A.E. Fuhs, USNPGS, given to SS2001, 11 December 1989.

14. Brown, A., "A Multi-Sensor Approach to Assuring GPS Integrity," *GPS World*, v.1, n.2, March/April 1990.

15. Enge, P.K., and others, "Combining Pseudoranges from GPS and Loran-C for Air Navigation," *Navigation*, v.37, n.1, Spring 1990.

16. Kalafus, R.M., "GPS Integrity Channel RTCA Working Group Recommendations," *Navigation*, v.36, n.1, Spring 1989.

17. Kinal, G.V., and Singh, J.P., "An International Geostationary Overlay for GPS and GLONASS," *Navigation*, v.37, n.1, Spring 1990.

18. Nagle, J., in "Milestones 1990--GPS in a Changing World," *GPS World*, v.2, n.1, January 1991.

19. Pietraszewski, D., "Differential GPS," presentation given to MCM Navigation AdHoc Working Group, 9 April 1990, Coast Guard Research and Development Center, Groton, CT.

20. Kremer, G.T., and others, "The Effect of Selective Availability on Differential GPS Corrections," *Navigation*, v.37, n.1., pp. 39-52, Spring 1990.

21. USCG Research and Development Center, letter 712200 to Commandant (G-NRN), Subject: Status of Prototype USCS DGPS Broadcasts from the Montauk Point, NY Radiobeacon, 12 March 1991.

22. Loomis, P., Kremer, G., and Reynolds, J., "Correction Algorithms for Differential GPS Reference Stations," *Navigation*, v.36, n.2, Summer 1989.

23. Hervig, K., and Fjaereide, H., "Applications of Differential GPS," *AGARD: Analysis, Design and Synthesis Methods for Guidance and Control Systems*, National Technical Information Service N90-29338/2, PC A21/MF AO3, June 1990.

24. Spalding, J., personal correspondence to author, 2 May 1991.

25. Buddenberg, R., "Development Options Proposal for Differential GPS Service Program," circulated paper, December 1990.

26. Wenzel, R., letter to R. Buddenberg, Subject: Review of DOP Draft, 15 January 1991.

27. USCG Research and Development Center, "Advanced NAVSTAR GPS Research and Development," Project Master Plan Narrative: Project No. 2200, Version 4, 12 June 1990.

28. U.S. DOT, Research and Special Programs Administration, Transportation Systems Center, DOT-CG-N-01-90, *U.S. Coast Guard Radionavigation System User Survey*, by A.S. Prabhakar, February 1990.

29. Wenzel, R., letter to author, Subject: DGPS and Radionavigation, January 1991.

30. Interview between D. Pietraszewski, USCG Research and Development Center, Groton, CT, and the author, 10 January 1991.

31. U.S. Coast Guard, *Tentative Operational Requirement for a Differential Global Positioning System,* Commandant (G-NRN), Washington, DC, 21 November 1990.

32. Gynther, J.W., and Smith, M.W., *Radio Aids to Navigation Requirements: 1988 Simulator Experiment*, USCG Research and Development Center (CG-D-08-90), December 1989.

33. Alsip, D., letter to author, 11 April 1991.

34. Price, R. I., anad Falvey, T.J., "The Coast Guard and Marine Traffic Engineering," Coast Guard Academy *Bulletin*, v.51, n.7, December 1989/January 1990.

35. Harrington, J.E., *Surveillance Techniques for the Vessel Traffic Service Systems of the U.S. Coast Guard*, Master's Thesis, Naval Postgraduate School, Monterey, CA, June 1990.

36. Bussey, J.E., LCDR, USCG, in "VTS New York Returns to the Air," U.S. Coast Guard *Bulletin*, by J. McGranachan, February 1991.

37. *GPS World*, "Global View," v.2, n.1, January 1991.

38. DeLoach, S.R., "Precise, Real-Time Dredge Positioning," *GPS World*, v.2, n.2, February 1991.

39. Defense Systems Management College, Fort Belvoir, VA, *Acquisition Strategy Guide*,July 1984.

40. Buddenberg, R., "The Internationalization of Radionavigation Systems," unpublished draft, April 1991.

41. Black, U., *Data Networks: Concepts, Theory, and Practice*, Prentice-Hall, 1989.

42. U.S. Department of Defense, *Computer-Aided Acquisition and Logistic Support(CALS) Program Implementation Guide*, Secretary of Defense DASD(S)CALS, Washington, DC, 20 December 1988.

43. Rogoff, M., "Electronic Charts in the Nineties," *Navigation*, v.37, n.4, Winter 1990-91.

44. Buddenberg, R., "Broadcast nodes for DGPS," white paper, 3 February 1991.

45. Commandant (G-NRN), "Advance Notice of Proposed Rule Making (ANPRM), 33 CFR 66," internal position paper, n.d.

46. Enge, P., and others, "Architecture for a Civil Integrity Network Using Inmarsat," *Proceedings of the Institute of Navigation GPS-90*, Institute of Navigation, Washington, DC, September 1990.

47. Klobuchar, J.A., "Ionospheric Effects on GPS," *GPS World*, v.2, n.4, April 1991.

48. U.S. Coast Guard, COMDTINST M16500.13, *Aids to Navigation Manual, Radionavigation*, 3 January 1989.

49. Alsip, D., letter to the author, 18 December 1990.

50. Alexander, L., letter to the author, Subject: Hyperfix, 20 February 1991.

51. Bogle, A.S., John E. Chance & Associates, letter to the author, 12 December 1990.

52. Lanigan, C.A., Pflieger, K., and Enge, P.K., "Real-Time Differential Global Positioning System (DGPS) Data Link Alternatives," *Proceedings of the Institute of Navigation GPS-90*, Institute of Navigation, Washington, DC, September 1990.

53. International Association of Lighthouse Authorities, Radionavigation Technical Committee, Systems Working Group, "Differential GPS," status report, September 1990.

54. Chapman, R., (ed.), *The World in Space*, United Nations, Prentice-Hall, 1982.

55. Graham, D.M., "Comsat Corporation: Globalizing Satellite Communications," *Sea Technology* v.32, n.5, May 1991.

56. Zachmann, G.W., "Differential GPS Transmissions By Geostationary L-Band Satellites," Sea Technology, n.d.

57. Schworer, W.J., III, *Nationwide Mobile Communication Systems*, Master's Thesis,Naval Postgraduate School, Monterey, CA, June 1990.

58. Feldman, D.A., Letts, M.A., and Wenzel, R.J., "The Coast Guard Two Pulse Loran-C Communications System," *Proceedings of the Institute of Navigation National Marine Meeting on Loran-C*, Institute of Navigation, Washington, DC, October 1975.

59. Pasupathy, S., "Minimum Shift Keying: A Spectrally Efficient Modulation," *IEEE Communications Magazine*, July 1979.

60. U.S. Coast Guard, DOT-CG-N-02-86, *Medium-Frequency Data Link for Differential NAVSTAR/GPS Broadcast*, by P.K. Enge, M.F. Ruane, and L. Sheynblatt, June 1986.

61. Enge, P.K., Kalafus, R.M., Ruane, M.F., "Differential Operation of the Global Positioning System," *IEEE Communications Magazine*, v.26, n.7, July 1988.

62. Telephone conversation between L.A. Miller, Marketing Manager, American Mobile Satellite Corporation, and the author, 5 June 1991.

63. Brown, A., "Extended Differential GPS," *Navigation*, v.36, n.3, Fall 1989.

64. Archibald, R.D., and Villoria, R.L., *Network-Based Management Systems (PERT/CPM)*, Wiley, New York, 1967.

65. Kavvadias, B., *Telecommunications Systems Cost-Effectiveness Analysis - a Quick and Practical Approach*, class paper for Prof. W.R. Gates, CM 4003, March 1989.

66. Joint Tactical Communication Office, Fort Monmouth, NJ, "*Cost-effectiveness Program Plan for Joint Tactical Communications- Life Cycle Costing*," v.II, 1982.

67. Seiler, K. III, *Introduction to Systems cost-Effectiveness*, Wiley-Interscience, 1968.

68. Kalafus, R. M., and others, "Differential Operation of NAVSTAR GPS," *Global Positioning System Papers published in Navigation*, v.II, Institute of Navigation, 1984.

69. U.S. Coast Guard, COMDTINST M4150.2, *Systems Acquisition Manual*, 21 January 1990.

70. U.S. Coast Guard, *Resource Prospectus for Differential GPS Navigation System*, RP#285.05, for BY 93; Commandant (G-NRN), Washington, DC, 15 March 1991.

71. Jones, J.V., *Engineering Design: Reliability, Maintainability, and Testability*, TAB Books, 1988.

72. *OMB Circular No A-94*, Executive Office of the President-Office of Management and Budget, Washington, DC, March 1972.

73. Beukers, J.M., "Developing a Commercial Market for GPS Receiving Equipment," *GPS World*, v.2, n.3, March 1991.

74. U.S. DOT, Research and Special Programs Administration, Transportation Systems Center, DOT-TSC-RSPA-83-11, *NAVSTAR GPS Simulation and Analysis Program*, by R. Kalafus, and others, December 1983.

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      Department of Electrical Engineering
      Worcester Polytechnic Institute
      100 Institute Rd.
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13.   Professor D. C. Boger   1
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      Naval Postgraduate School
      Monterey, CA 93943-5002